June, 1911 Chemical Series Vol. I, No. 10

Biological & Medical Series

Memoirs of the Department of Agriculture in India

WATER REQUIREMENTS OF CROPS IN INDIA—II

BY

J. WALTER LEATHER, Ph.D., F.I.C

Imperial Agricultural Chemist

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PUBLISHED FOR
THE IMPERIAL DEPARTMENT OF AGRICULTURE IN INDIA

BY
THACKER, SPINK & CO., CALCUTTA
W. THACKER & CO., 2, CREED LANE, LONDON

Price, Rs. 2-8

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PREFACE.

This Memoir forms a sequel to No. 8 and provides further information regarding the water requirements of crops in India, as determined in soils other than that at Pusa, as also the results of determinations carried out in the field.

Nearly the whole of the experimental work has been executed by Messrs. B. M. Amin, B.A., A. V. Iyer, B.A., K. S. Viswanadham, B.A., and D. N. Chatterji, B.A., B.SC., Assistants in the Chemical Section of this Institute, and by Babus Ganga Parshad Pande and Nand Kishore Saksena of the Cawnpore Agricultural Station. I desire to take this opportunity of acknowledging the care which they have bestowed upon the work.

My acknowledgments are also due to Mr. B. C. Burt, Deputy Director of Agriculture, United Provinces, for valuable assistance in connection with the Cawnpore section of the work.

Pusa,
January, 1911.

J. W. L.

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WATER REQUIREMENTS OF CROPS IN INDIA—II.

BY

J. WALTER LEATHER, Ph.D., F.I.C., etc.,

Imperial Agricultural Chemist.

Introductory.

In Memoir No. 8 (Chemical Series) the results which had been obtained by measuring the amounts of water transpired by plants when grown by "pot-culture" methods were detailed, and the plan of the experiments was set out on page 143. It was there explained, p. 144, that in developing the work it had been decided to grow (*i*) a number of plants in one sort of soil, and (*ii*) the same plant in a variety of soils, but that details regarding the latter would be published separately. This course was necessitated by the fact that, although this section of the work was in part completed in the monsoon season of 1908, the cultures of the following cold weather season were a failure, chiefly owing to want of experience with some of the new soils. The difficulty was related to the physical properties of these soils and this matter will be explained subsequently. The test with the cold weather crops was repeated in the season 1909-10 and the whole data may now be published. In addition to this part of the investigation, it was felt to be desirable, since most of the plants mentioned in Memoir No. 8 had been cultivated in small jars holding about 15 kilos of soil, to grow some of them again in the large jars containing about 50 kilos of soil, in order to check the former transpiration ratios, and this was done in the cold weather season 1909-10. Part I of this memoir is devoted to this section of the work and to a discussion of the results.

In addition to these estimates of water requirements of crops by pot-culture methods, it occurred to me some four years ago to try to make observations in the field on the same subject.

It is generally acknowledged that results obtained by pot-cultures should be, when possible, verified by similar experiments in the field, and however great the difficulty in estimating the water requirements of crops in this way, it was evident that if the pot-culture estimate could be even approximately checked, such confirmation would possess considerable value. Details regarding the method employed, the data obtained and the deductions which may be made therefrom are set out in Part II.

The Memoir also includes certain arguments and deductions in regard to movements of water in soils, and the importance of a method for the estimation of the rate at which water can move through soils is emphasised.

PART I.

Pot-Cultures.

As briefly indicated above, specimens of our field crops have been grown in the pot-culture house in order to ascertain the amount of water transpired from the initial stage of growth until fully ripe.

As regards details of the method, the reader may be referred to pp. 137-142 of Memoir No. 8 (Chemical Series), but some further notes are here of importance because of the fact that difficulties were experienced in the use of some of the soils.

Filling the jar.—Soils containing but little clay are best filled into the jars in a damped condition as previously described.* Thus the Shillong soil, which contains a high proportion of organic matter, and the Palur soil, could be filled in and pressed down into the jar in the same manner as the calcareous Pusa soil ; but the highly argillaceous Black Cotton soil from Akola apparently became too closely packed when filled in this manner, and it was found necessary to only *shake* it, in the damped condition (15% water) into the jars. This was undoubtedly due to the fact that

* Loc. cit. p. 138.

this soil swells in quite an extraordinary manner when wet and hence the necessity for allowing a good deal more "interspace" than for the other soils.

Mode of adding Water.—The water used, clean well water, was for the most part added through the cylinders,* but this practice had to be varied in certain cases.

One of the most striking difficulties which we met with was related to the secondary root system of maize. The cereals, millets, etc., after producing the radicle and one or two leaves, develop the secondary "adventitious" root system from the node at the base of the first leaf. Shortly after this, the radicle stem below the first node ceases to functionate and dies off, and the plant depends on its secondary root system. It follows that if the surface soil, into which this secondary root penetrates, is moist, the further growth of the plant is assured: if, on the other hand, the surface soil is air-dry, this secondary root system cannot develop or at least may not get down to the moist soil before the primary stem has died off: the plant then withers. Now the rate at which moisture moves through the Black Cotton soil and the Shillong soil is apparently so slow that, although there was a fairly liberal allowance of water, 30″ and 25″ respectively, in these soils *as a whole* in the first and second seasons, they became air-dry *at the surface* for about 3″ deep, and the maize plants could not get their secondary roots through this dry soil before the lower part of the stem began to fail. In the monsoon of 1908 some of the maize had to be re-sown on this account, and all plants in the three soils from Akola, Shillong and Palur, respectively, had to be assisted. This was done by forming a small heap of soil round each plant and keeping this wet by surface additions of water until the plant had developed sufficiently to be independent in this respect. This procedure did not affect the transpiration ratio in any measurable degree because transpiration only becomes considerable after the secondary roots have made a vigorous start. Subsequently the drier the surface soil the better, since it was desired to reduce the loss due to simple evaporation as far as

* Loc. cit. p. 138

possible; hence all water was subsequently added through the irrigation cylinders.

Bearing this difficulty in mind, it was decided to circumvent it in the cold weather of 1909-10 if possible by a different arrangement. What was obviously desired was to maintain the surface of these soils thoroughly moist; but if this were done in an unprotected manner, the direct loss by evaporation from the soil would undoubtedly be very high, and the error due to this would also be high. This point has been fully dealt with in the preceding Memoir (No. 8, p. 140). For reasons there explained close covers seemed to be objectionable; what was wanted was a cover which would, on the one hand, allow aeration of the surface soil, whilst on the other, it would prevent in a great measure the excessive evaporation. A layer of coarse gravel seemed to meet these requirements, for aeration would be very perfect, whilst the amount of water that would be conveyed over its surface by surface tension would be negligible and that which would pass out by diffusion of water vapour would probably be also small. Over the soil surface a single layer of rather coarse ($\frac{1}{4}''$—$\frac{1}{2}''$) pebbles and over this another inch of $\frac{1}{8}''$—$\frac{1}{4}''$ gravel was laid. This "cover" served the end in view excellently; the growth of the plants left nothing to be desired, and the loss by evaporation was reduced to *less than* one-half that of the Pusa soil, instead of being much higher, whilst the soil was maintained quite damp to its surface.

A third deviation in respect of certain of these jars was found necessary. Some of the plants transpired upwards of 4 kilos of water per diem during their most vigorous stage, and it was found during this period that if the whole of this water were added in the morning after recording the weights, as has been the general custom, the plants ran short during the afternoon. It became necessary therefore to add water twice a day to two jars of Akola soil and to two of Pusa soil, the plants being sarson in each case. Moreover, to two of the Akola soil jars it was necessary, during the period of most vigorous growth, to add water at the surface. This introduced a further source

of error, for this addition of water through the gravel necessarily left the latter wet and would hence occasion a greater loss by evaporation from these jars than from the blank jars. It was found, however, that this excess loss was far less than we anticipated; apparently the gravel when wet held so little water that when this evaporated the loss from soil and gravel was not much greater than when the gravel was air-dry, and the error became negligible. In this respect reference may be made to Statements Nos. II & III in which the data relating to wheat and sarson are set out: from the manured wheat jars about 180 kilos of water were transpired against 11 evaporated: from the corresponding sarson jars the respective figures are about 130 against 8, so that whatever error might be introduced by wetting the gravel periodically during a part of the period of growth, such error could not affect the transpiration ratio materially. As has been said, however, the extra loss from the wet gravel was found experimentally to be only nominal.

Sowing.—Owing to the employment of the gravel it was anticipated that some provision would be necessary to keep the gravel off the plant in its initial stage. This proved by subsequent trial to be unnecessary, for if seeds are sown in the soil, the plantling is strong enough to force its way quite well through the $1\frac{1}{2}''$ to $2''$ of gravel. But at the time of sowing the jars, no risks of failure could be run, and hence the following device was employed. For each seed a small tube of brown paper, about $2''$ long by $\frac{1}{2}''$ diam. was inserted through the gravel on to the soil surface, and the seed placed in the soil. After the plants had come through, these paper cylinders were removed. Although subsequently found unnecessary, the device answered its purpose very well, though great care had to be exercised when removing the paper cylinders in order to avoid damaging the young plant.

Evaporation through the sides of jars.—Before passing to a consideration of the data obtained during the two seasons, reference may be made to some measurements of the amount of water which vapourises through the sides of these cultivation jars.

Since the publication of Memoir No. 8, a correspondent has raised the question whether such evaporation could have introduced any material error. Now, as was explained in that publication (p. 140), jars of soil of the same degree of moisture as the jars carrying plants are maintained in order to estimate the loss of water from the soil as distinct from the loss due to transpiration which the plant-bearing jars suffered. Since the jars are glazed no serious loss by vapourisation through their sides could very well take place, but in any case whatever such loss of water might be, it was necessarily included in the loss from the blank jars. It was also explained (p. 141) that the estimate of water lost by evaporation from the soil was open to some error, because no two jars of moist soil will evaporate exactly equal amounts. Moreover it has to be recognised in all this work that the loss by *evaporation* from soil bearing large leafy plants will presumably be less than if the same soil were freely exposed to the air. Indeed the method of estimating the loss from the soil, and hence the amount of water transpired, is only correct within certain limits. But to illustrate in how far its error affects our final result, namely, the transpiration ratio, take the case of wheat grown in Akola soil (Statement No. II). If the soil had evaporated 25 per cent. less than was estimated by the blank jars, the ratio for jar No. 13 (small plants) would become 945 instead of 849, whilst in the same way, the ratio for jar No. 19 (large plants) would become 428 instead of 422. As was pointed out previously (p. 176) the ratio for poorly developed plants is of comparatively little consequence, whilst the error we are discussing hardly affects that for well-grown ones.

However, inasmuch as the question of the amount of water which evaporates through the sides of these cultivation jars was raised, some measurements of its amount were made. To this end the following method was adopted. Stout india-rubber sheet was tied over the top of four jars, two of which contained Pusa soil with 20 per cent. water, and two Akola soil with 40 per cent. water; the daily loss was then recorded for a fortnight in the hot weather, *i.e.*, when such loss would be maximum, and was

found to be ·05, ·015, ·03, ·02 kilo. per day. The daily loss from these jars *uncovered* had been ·159, ·109, ·122, ·121 kilo. respectively. It is thus seen that whilst the loss is measurable, it is certainly not a source of error which could affect any deductions that may be made from the experiments.

The plan of the experiments.—As explained briefly in the Introduction, the transpiration ratio has been determined for (*a*) plants grown in a variety of soils in order to ascertain whether the nature of the soil had any effect on the result, and (*b*) plants grown in large jars of Pusa soil in order to ascertain the effect of the larger mass of soil. In addition to the latter, sugar-cane has been grown in 1910 in large jars (size E) in order to estimate its water requirements. In the section (*a*) four soils, namely, from Pusa, Akola, Shillong and Palur, were used in the monsoon of 1908 when maize was the only plant grown: both large and small jars were here included. In the cold weather season of 1909-10 the first three soils were again used and several varieties of crop grown; only the largest jars were employed. In the section (*b*) the same seven crops were experimented with as were grown in the preceding cold weather. The whole series may be conveniently set out in the following manner. The letters (*a*) and (*b*) indicate the sections of the work for which each crop served:—

Season.	Pusa soil.	Akola soil.	Shillong soil.	Palur soil.
Monsoon 1908 ...	Maize (*a*).	Maize (*a*).	Maize (*a*).	Maize (*a*).
Cold weather, 1909-1910	Wheat (*a* & *b*). Sarson (*a* & *b*). Linseed (*a* & *b*). Peas (*b*). Barley (*b*). Oats (*b*). Gram (*b*).	Wheat (*a*). Sarson (*a*). Linseed (*a*).	Wheat (*a*).	..
February–December, 1910 ..	Sugar-cane.	..	..	..

Data obtained.—The Statements Nos. I—VI set out details regarding the sizes of jars used, the quantities of soil, proportion

of moisture maintained, whether fertilizers were added or not and in what quantity, besides the weights of crops and amounts of water transpired, etc., and for information regarding these matters reference must be made to them. It will be seen that in al. cases some jars of soil were unmanured, in some, "incomplete" fertilizers were used, and again in all cases some jars of soil received a "complete" fertilizer. In respect of the term "complete" manure, since the addition of potash salts to the Pusa soil has never proved an advantage, a mixture of nitrogenous and phosphatic manure is a "complete" fertilizer for this soil.

As in the previous Memoir, the number given to each plate or chart is that of the statement to which it is related.

The Nature of the Soils.—The following details regarding the several soils will be of interest.

The Pusa Soil.—Behar, where the Pusa Institute is situated, is in the Gangetic alluvium, and its soil is as free from pebbles and other stones as is the rest of that geological area. It is also of unknown depth. The Pusa soil is exceptionally fine and contains a low proportion of true clay. It is highly calcareous, containing from 30 to 40 per cent. of calcium carbonate. Of organic matter it contains as low a proportion as Indian soils in the plains so commonly do; it is very poor in readily available phosphate and the application of superphosphate in conjunction with a nitrogenous manure increases the outturn to an unusual degree: potash salts have no effect on the crop. In relation to water, our field tests have shown that it holds about 25 lbs. per cubic foot after drainage has ceased, and crops are able to utilise as much as three or four-fifths of this. Consequently heavy cold weather crops may be grown on much of this land without the assistance of rain or irrigation. Reference to the field experiments (page 245 of this Memoir) shows that some of the crops of the cold weather of 1909-10 weighed 5,000 or 6,000 lbs. of total produce per acre, whilst the rainfall was only ·22″. It is indeed probable that few soils exist which hold such stores of water in a manner readily available to the crop. The following are the analytical data:—

Elutriation.		Chemical analysis.	
Mean diam. of particles mm.	Per cent.		
<·002	3·9	Insoluble silicates and sand	59·05
·002—·004	4·8	Ferric oxide	2·30
·004—·008	7·7	Alumina	3·43
·008—·016	9·4	Calcium oxide	17·57
·016—·032	40·4	Magnesia	·62
·032—·5	34·4	Potash	·45
		Soda	·20
	100·6	Phosphoric acid	·10
		Sulphuric ,,	·01
		Carbonic ,,	14·26
		Organic matter and combined water	1·28
			99·27
		Organic carbon	·46
		Organic nitrogen	·07
		Available phosphoric acid*	·0001
		Available potash	·005

The Akola Soil.—Akola, in the Berars, is situated in a tract of typical "Black Cotton" soil. The chief general characteristics of this soil are (*a*) its colour, this being a dark brown verging on black, (*b*) a very high content of argillaceous substance, and (*c*) a great increase of volume when wetted or corresponding decrease when dried: it usually contains one to three or more per cent. of calcium carbonate. How much water this soil contains after drainage has ceased is not known, but since for the pot-cultures of 1909-10, 40 per cent. water was maintained and this did not cause any drainage, it is certainly greater than this. On the other hand, judging by pot-culture experience at Pusa, which is, however, not very reliable for the purpose, plants cannot obtain nearly all this water, and after the moisture has fallen somewhat, water seems to move through it under the influence of surface tension only very slowly.† Owing to its highly argillaceous character, it opens out into deep fissures on drying, and it is naturally assumed that it loses much of its moisture in this way: on the other hand, after the surface 2″ or 3″ has dried and provided fissures are prevented, it was found in the pot-culture work to lose only about one-half as much water as the Pusa soil, even when the moisture proportions were 30 and 20 per cent respectively. It is probable therefore that its defect as a reservoir of moisture for plants lies, not so much in

* Determined by Dyer's method.

† This is supported by experience at Ota

the rapid loss of water to the air, though this certainly would apply to the surface 2″ or 3″, but rather to an inability to permit its great store of water to flow to the plant. The following are the analytical data :—

Elutriation.		Chemical analysis.	
Mean diam. of particles mm.	Per cent.		
< ·002	10·1	Insoluble silicates and sand	56·11
·002 — ·004	17·1	Ferric oxide	9·83
·004 — ·008	9·6	Alumina	10·68
·008 — ·016	12·7	Calcium oxide	6·59
·016 — ·032	24·4	Magnesia	2·51
> ·032	17·0	Potash	·37
		Soda	·23
	90·9	Phosphoric acid	·08
		Carbonic acid	4·18
		Organic matter and combined water	9·42
			100·00
		Organic carbon	·81
		Organic nitrogen	·03
		Available phosphoric acid	·007
		Available potash	·016

The Shillong Soil.—This is a highly ferruginous soil containing much organic matter. Shillong being situated in the Khasi Hills, enjoys a cool climate ; the rainfall is heavy and fairly well distributed. Consequently an accumulation of organic matter might be anticipated. It is very friable, will hold a large amount of water and drains readily, but judging by our limited experience with it at Pusa, it loses water rapidly to the atmosphere. The following are the analytical data :—

Elutriation.		Chemical analysis.	
Mean diam. of particles mm.	Per cent.		
< ·002	3·4	Insoluble silicates and sand	72·94
·002—·004	4·4	Ferric oxide	7·00
·004—·008	5·1	Alumina	9·65
·008 —·016	8·1	Calcium oxide	·02
·016—·032	19·5	Magnesia	·32
> ·032	54·9	Potash	·35
		Phosphoric acid	·07
	95·4	Organic matter and combined water	7·86
			98·22
		Organic carbon	2·63
		Organic nitrogen	·15
		Available phosphoric acid	·0082
		Available potash	·0058

The Palur Soil.—This soil exhibits no very special characteristics except that, although sandy, the elutriation figures perhaps indicate it as more sandy than it really is.

The following are the analytical data :—

Elutriation.		Chemical analysis.	
Mean diam. of particles mm.	Per cent.		
<·002	1·7	Insoluble silicates and sand	90·68
·002—·004	3·4	Ferric oxide	2·47
·004—·008	2·8	Alumina	3·72
·008—·016	3·8	Calcium oxide ...	·63
·016—·032	14·9	Magnesia	·34
>·032	71·6	Potash	·19
	98·2	Soda	·05
		Phosphoric acid	·04
		Organic matter and combined water	1·88
			100·00
		Organic carbon	·54
		Organic nitrogen	·054
		Available phosphoric acid	·027
		Available potash	·011

STATEMENT I.

Zea Mays (Maize), 1908.

Jar No.	Jar size.	Soil per Jar Kilos.	Water in soil per cent.	Manures.	Date of Sowing.	Date of Harvest.	Dry Crop Seed Grms.	Dry Crop Total Grms.	Water transpired. Kilos.	Ratio.
				Pusa Soil.						
×	A—9" diam. × 12" deep.	14	20	Blank jar			...	...	17·80	...
2		14	20	*Nil*	8-6-08	17-9-08	Nil	31·4	14·02	446
3		14	20				Nil	31·5	12·51	397
4		14	20	N	8-6-08	17-9-08	Nil	30·4	14·58	480
5		14	20				·2	32·8	13·01	397
6		14	20	N, P	8-6-08	17-9-08	Nil	49·9	22·41	444
7		14	20				·5	65·6	27·41	422
				Alola Soil.						
50	B—12" diam. × 12" deep. A—9" diam. × 12" deep.	12	30	Blank jar			...	...	3·5	...
51		12	30	*Nil*	18-6-08	26-9-08	Nil	8·4	3·68	438
52		12	30				Nil	9·3	4·24	456
53		12	30	N	18-6-08	16-10-08	1·1	12·5	9·15	732
54		12	30				Nil	14·8	8·35	564
55		12	30	N, P	18-6-08	26-9-08	3·5	52·9	19·34	366
56		12	30				2·3	57·9	19·94	344
57		12	30	N, P, K	18-6-08	26-9-08	1·6	51·3	16·98	331
58		12	30				2·4	59·8	20·85	349
×	B—12" diam. × 12" deep. A—9" diam. × 12" deep.	42·5	30	Blank jar			...	...	5·40	...
702		42·5	30	*Nil*	4-7-08	10-10-08	3·6	33·6	18·59	553
703		42·5	30				Nil	11·9	9·57	804
704		42·5	30	N	4-7-08	10-10-08	4·5	35·2	17·29	491
705		42·5	30				6·4	46·4	26·35	568
706		42·5	30	N, P	4-7-08	10-10-08	14·4	137·8	44·27	321
707		42·5	30				21·4	120·7	37·42	310
708		42·5	30	N, P, K	4-7-08	10-10-08	7·5	103·1	39·73	385
709		42·5	30				31·4	114·1	39·79	349

STATEMENT I—(*contd.*)

Jar No.	Jar size.	Soil per Jar Kilos.	Water in soil per cent.	Manures.	Date of Sowing.	Date of Harvest.	Dry crop Seed Grms.	Dry crop Total Grms.	Water transpired Kilos.	Ratio.
				Shillong Soil.						
59	D—12″ diam. × 16″ deep.	12	25	Blank jar	...	...	...	...	(7·5)	...
60		12	25	*Nil*	10-7-08	26-10-08	1·9	24·4	14·13	579
61		12	25	*Nil*			7·3	27·1	17·58	649
62		12	25	N	10-7-08	26-10-08	14·3	38·5	17·91	465
63		12	25	N			2·6	31·4	19·25	613
64		12	25	N, P	10-7-08	16-10-08	19·6	82·9	30·77	371
65		12	25	N, P			22·9	90·6	32·08	354
601		32	25	Blank jar	...	...	...	...	(10·0)	...
602		32	25	*Nil*	9-7-08	26-10-08	20·8	86·9	45·27	521
603		32	25	*Nil*			33·3	96·6	39·76	412
604		32	25	N	9-7-08	26-10-08	4·1	81·8	41·05	502
605		32	25	N			5·3	60·0	32·37	540
606		32	25	N, P	9-7-08	10-10-08	113·0	236·5	70·11	296
607		32	25	N, P			112·1	239·4	66·50	278
608		32	25	N, P, K	9-7-08	10-10-08	115·1	268·3	78·40	292
609		32	25	N, P, K			103·1	242·4	77·51	320
				Palur Soil.						
501	C—9″ diam. × 22″ deep.	32	20	Blank jar	...	...	...	...	(5·0)	...
502		32	20	*Nil*	30-6-08	26-9-08	12·1	88·6	38·25	432
503		32	20	*Nil*			8·2	108·5	42·60	393
504		32	20	N	30-6-08	26-9-08	32·7	220·7	54·31	246
505		32	20	N			32·3	226·9	62·52	276
506		32	20	N, P	30-6-08	26-9-08	37·9	198·4	73·05	368
507		32	20	N, P			20·9	189·8	67·99	358
508		32	20	N, P, K	30-6-08	26-9-08	15·5	156·3	58·43	374
509		32	20	N, P, K			13·7	145·3	54·56	376

Note.—N = Ca $(NO_3)_2$ = ·005 grm. N ; P = Superphosphate = ·01 grm. soluble P_2O_5 ; K = K_2SO_4 = ·005 grm. K_2O per 100 grms. soil.

STATEMENT II.

Triticum sat. (Wheat) 1909-10.

Jar No.	Jar size.	Soil per Jar Kilos.	Water in soil per cent.	Manures.	Date of Sowing.	Date of Harvest.	Dry crop Seed Grms.	Dry crop Total Grms.	Water transpired Kilos.	Ratio.
				Pusa Soil.						
×	E—12″ diam. × 22″ deep.	48	20	Blank jars	...	...	...	...	(18·59)	
27		48	20	*Nil*	2-11-09	1-4-10	20·10	75·82	45·09	595
28		48	20	*Nil*			23·47	96·56	55·05	570
41		48	20	N, P	2-11-09	1-4-10	113·80	380·70	187·59	493
42		48	20	N, P			131·40	429·70	214·10	498
				Akola Soil.						
×	E—12″ diam. × 22″ deep.	41·6) 43·2)	40	Blank jars	...	...	...	...	(11·30·	
13		43·4	40	*Nil*	7-11-09	12-4-10	4·49	28·90	24·50	849
14		45·0	40	*Nil*			4·85	27·29	22·79	835
19		41·0	40	N, P, K	7-11-09	6-4-10	106·50	428·70	181·10	422
20		45·9	40	N, P, K			116·60	400·80	183·79	459

STATEMENT II—(*concld.*)

Jar No.	Jar size.	Soil per Jar Kilos.	Water in soil per cent	Manures.	Date of Sowing.	Date of Harvest.	Dry Crop Seed Grms.	Dry Crop Total Grms.	Water transpired Kilos.	Ratio.
				Shillong Soil.						
×	E—12" diam. × 22" deep.	45·0 / 44·0	30	Blank jars					(16·90)	
5		44·4	30	*Nil*	2-11-09	12-4-10	2·49	13·95	8·49	587
6		42·8	30	*Nil*	2-11-09	12-4-10	1·24	6·78	3·16	466
9		43·9	30	N, P, K	2-11-09	12-4-10	63·99	179·49	101·93	568
10		43·5	30	N, P, K	2-11-09	14-4-10	65·42	189·82	112·32	592

Note.—N = $Ca(NO_3)_2$ = ·005 grm. N ; P = superphosphate = ·01 grm. soluble P_2O_5 ; K = K_2SO_4 = ·005 grm. K_2O per 100 grms. soil.

STATEMENT III.

BRASSICA CAMPESTRIS (SARSON) 1909-10.

Jar. No.	Jar size.	Soil per Jar Kilos.	Water in soil per cent.	Manures.	Date of Sowing.	Date of Harvest.	Dry Crop Seed Grms.	Dry Crop Total Grms.	Water transpired Kilos.	Ratio.
				Pusa Soil.						
39	E—12" diam. × 22" deep.	48	20	Blank jar					(13·60)	
40		48	20	*Nil*	2-11-09	26-2-10	9·74	38·40	17·95	472
53		48	20	*Nil*	2-11-09	26-2-10	9·74	37·91	18·58	490
54		48	20	N, P	2-11-09	26-2-10	85·65	266·35	104·40	392
		48	20	N, P	2-11-09	26-2-10	86·87	267·37	100·69	377
				Mola Soil.						
	E—12" diam. 22" deep.	41·6 / 43·2	40	Blank jars	...				(8·00)	
15		42·2	40	*Nil*	7-11-09	7-3-10	14·08	50·89	32·05	591
16		43·1	40	*Nil* ...	7-11-09	11-3-10	9·83	38·00	23·41	616
21		42·7	40	N, P, K	7-11-09	7-3-10	88·94	275·64	127·94	464
22		43·2	40	N, P, K	7-11-09	11-3-10	79·69	282·39	139·93	495

Note.—N = $Ca(NO_3)_2$ = ·005 grm. N ; P = Superphosphate = ·01 grm. soluble P_2O_5 ; K = K_2SO_4 = ·005 grm. K_2O per 100 grms. soil.

STATEMENT IV.

LINUM USITATISSIMUM (LINSEED) 1909-10.

Jar No.	Jar size.	Soil per Jar Kilos.	Water in soil per cent.	Manures.	Date of Sowing.	Date of Harvest.	Dry Crop Seed Grms.	Dry Crop Total Grms.	Water transpired Kilos.	Ratio.
				Pusa Soil						
×	E—12" diam. × 22" deep.	48	20	Blank jar					(16·86)	
37		48	20	*Nil*	2-11-09	21-3-10	10·97	45·25	41·72	922
38		48	20	*Nil*	2-11-09	21-3-10	5·72	22·86	28·97	1267
51		48	20	N, P	2-11-09	21-3-10	36·17	135·98	92·49	680
52		48	20	N, P	2-11-09	21-3-10	27·66	123·25	72·31	587

STATEMENT IV—(*concld.*)

Jar No.	Jar size.	Soil per Jar Kilos.	Water in soil per cent.	Manures.	Date of Sowing.	Date of Harvest.	Dry Crop Seed Grms.	Dry Crop Total Grms.	Water transpired Kilos.	Ratio.
				Akola Soil.						
	E—12″ diam. 22″ deep.	41·6	40	Blank jars	...	...	...	...	(9·60)	...
		43·2								
17		43·4	40	*Nil* ...	7-11-09	27-3-10	2·47	9·61	11·83	1231
18		43·1	40	*Nil* ...	7-11-09	27-3-10	1·90	7·63	7·87	1020
23		43·4	40	N, P, K ...	7-11-09	25-3-10	26·55	88·76	70·77	797
24		45·0	40	N, P, K ...	7-11-09	25-3-10	31·30	107·47	82·87	777

Note.—N = Ca $(NO_3)_2$ = ·005 grm. N ; P = Superphosphate = ·01 grm. soluble P_2O_5 K = K_2SO_4 = ·005 grm. K_2O per 100 grms. soil.

STATEMENT V.

Other Crops in Pusa Soil 1909-10.

Jar No.	Jar size.	Soil per Jar Kilos.	Water in soil per cent.	Manures.	Date of Sowing.	Date of Harvest.	Dry Crop Seed Grms.	Dry Crop Total Grms.	Water transpired Kilos	Ratio.
				Hordeum vulg. (*Barley*).						
×	E—12″ diam. 22″ deep.	48	20	Blank jar	...	...	...	...	(16·50)	...
29		48	20	*Nil*	2-11-09	17-3-10	30·76	75·54	36·66	485
30		48	20	*Nil*	2-11-09	17-3-10	29·07	71·27	29.36	412
43		48	20	N, P	2-11-09	23-3-10	125·20	342·20	157·00	459
44		48	20	N, P	2-11-09	23-3-10	146·40	382·40	172·40	451
				Avena sat. (*Oats*).						
×	E—12″ diam. 22″ deep.	48	20	Blank jar	...	...	...	...	(16·30)	...
31		48	20	*Nil*	2-11-09	19-3-10	31·61	81·42	39·45	485
32		48	20	*Nil*	2-11-09	19-3-10	23·98	58·12	29·10	501
45		48	20	N, P	2-11-09	17-3-10	123·60	275·40	103·29	375
46		48	20	N, P	2-11-09	17-3-10	132·90	292·40	117·34	401
				Cicer arietinum. (*Gram*).						
×	E—12″ diam. 22″ deep.	48	20	Blank jar	...	...	...	...	(17·7)	...
35		48	20	*Nil*	2-11-09	24-3-10	18·11	42·66	43·74	1025
36		48	20	*Nil*	2-11-09	29-3-10	12·96	32·96	46·41	1408
49		48	20	N, P	2-11-09	24-3-10	101·00	271·20	175·85	648
50		48	20	N, P	2-11-09	24-3-10	97·11	247·40	166·17	672
				Pisum sat. (*Peas*).						
×	E—12″ diam. 22″ deep.	48	20	Blank jar	...	...	...	...	(15·20)	...
33		48	20	*Nil*	2-11-09	7-3-10	14·57	38·54	31·36	814
34		48	20	*Nil*	2-11-09	7-3-10	13.28	37·72	30·49	808
47		48	20	N, P	2-11-09	14-3-10	66·36	243·46	138·81	570
48		48	20	N, P	2-11-09	14-3-10	45·94	221·14	137·25	621

Note.—N = Ca $(NO_3)_2$ = ·005 grm. N ; P = Superphosphate = ·01 grm. soluble P_2O_5 per 100 grms. soil.

STATEMENT VI(*a*.)

Sugar-cane grown in Pusa Soil 1910.

Jar No.	Size of Jar.	Soil per Jar Kilos.	Water in soil per cent.	Manures.	Date of Planting.	Date of Harvest.	Total dry matter Grms.	Water transpired Kilos.	Ratio.
55	E 12" diameter × 22" deep.	About 47 kilos Pusa soil.	20	Blank jars.	8th and 9th March 1910.	9th and 10th December 1910		(25·99)	
56			20					(20·19)	
57			20	*Nil.*			241	113·58	471
58			20				490	149·46	305
59			20	Farm manure			333	128·47	386
60			20				576	167·60	291
61			20	Farm manure and Superphosphate.			547	164·98	302
62			20				429	164·10	383
63			20	Calcium Nitrate			454	134·26	296
64			20				418	137·46	329
65			20	Calcium Nitrate and Superphosphate.			856	181·18	212
66			20				950	201·94	213
67			20	Oil-cake.			562	176·15	313
68			20				556	188·85	340
69			20	Oil-cake and Superphosphate.			508	184·71	364
70			20				669	208·33	311

Note.– Nitrogen in manure used = ·005 parts : P_2O_5 = ·005 parts per 100 parts soil.

STATEMENT No. VI (*b*).

Sugar-cane grown in Pusa Soil 1910.

Jar No.	Manures.	Harvest Weight.		Juice.				
		Clean cane. Grms.	Leaves Grms.	Grms.	Sp. gr.	Total solids Brix hydr.	Grms. sugar per 100 Grms. juice.	Grms. invert sugar per 100 Grms juice.
57	*Nil*	191	326	110	1·0830	20·27	18·34	·76
58		808	454	524	1·0882	21·50	20·21	·64
59	Farm manure	482	397	270	1·0854	20·78	19·66	·84
60		1,020	553	668	1·0830	20·28	18·80	·67
61	Farm manure and Superphosphate.	978	539	614	1·0892	21·47	20·73	·47
62		609	497	367	1·0893	21·47	21·02	·55
63	Calcium Nitrate	723	468	432	1·0907	21·87	21·56	·53
64		623	454	397	1·0955	22·87	22·51	·57
65	Calcium Nitrate and Superphosphate.	1,461	837	988	1·0977	23·37	22·90	·48
66		1,582	893	995	1·1003	23·97	23·10	·60
67	Oil-cake	765	609	434	1·1010	24·07	22·90	·65
68		893	567	577	1·0920	22·17	21·41	·51
69	Oil-cake and Superphosphate.	666	553	422	1·0900	21·67	21·05	·58
70		977	723	593	1·0940	22·37	21·70	·47

CHART Ia.

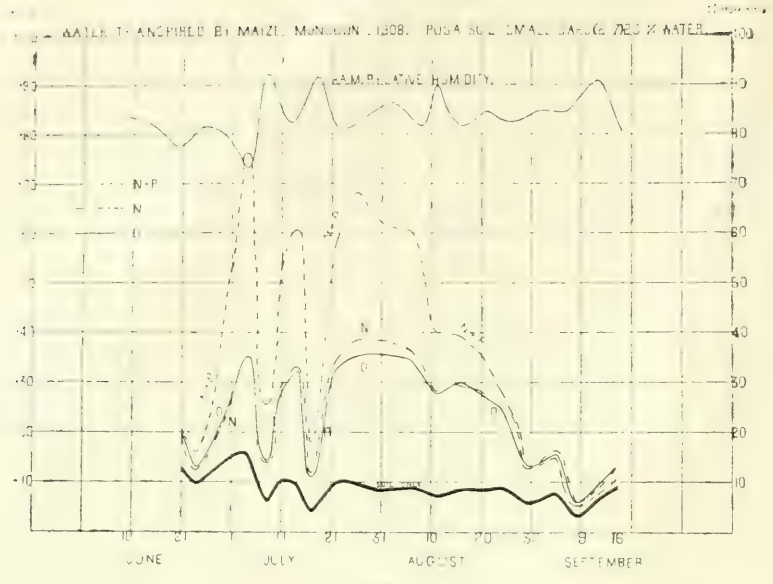
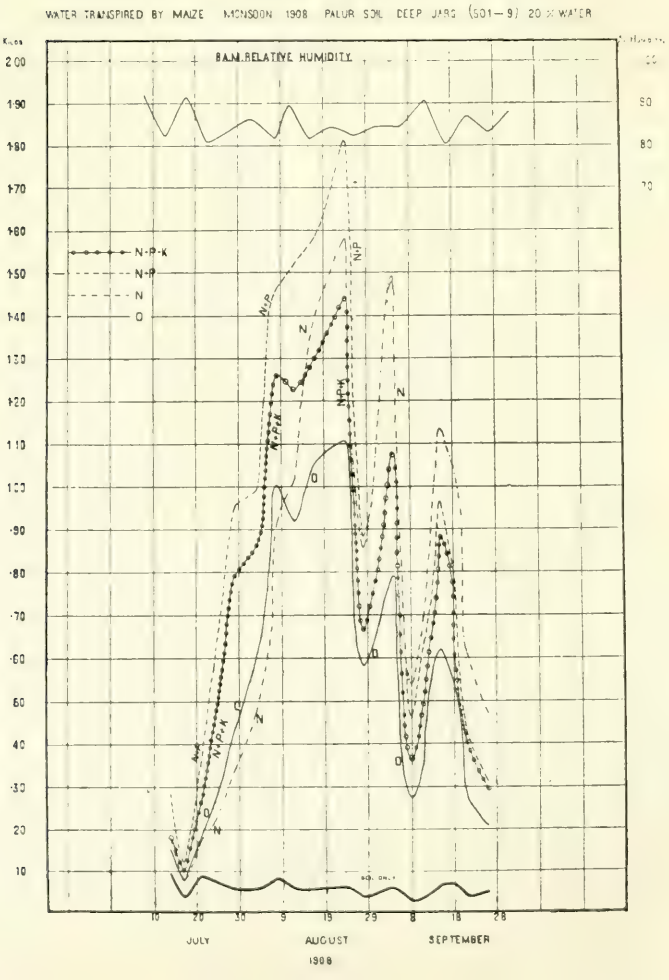


CHART If.



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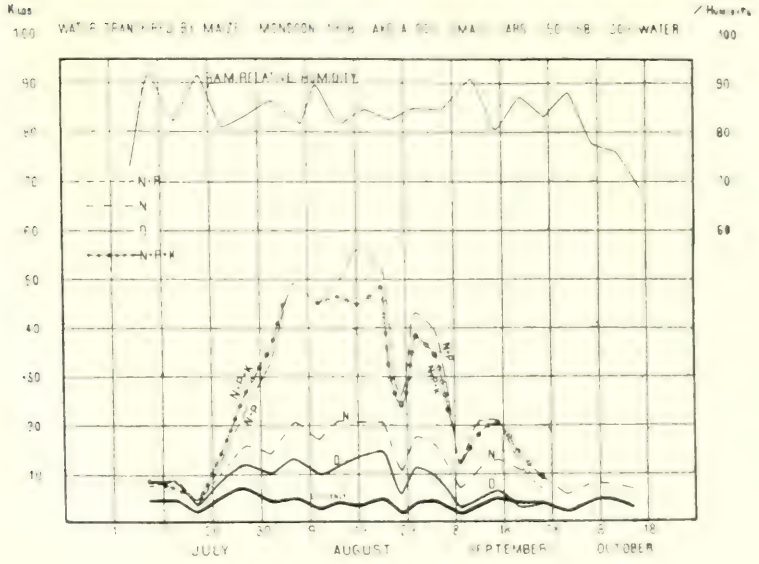


CHART Ic.

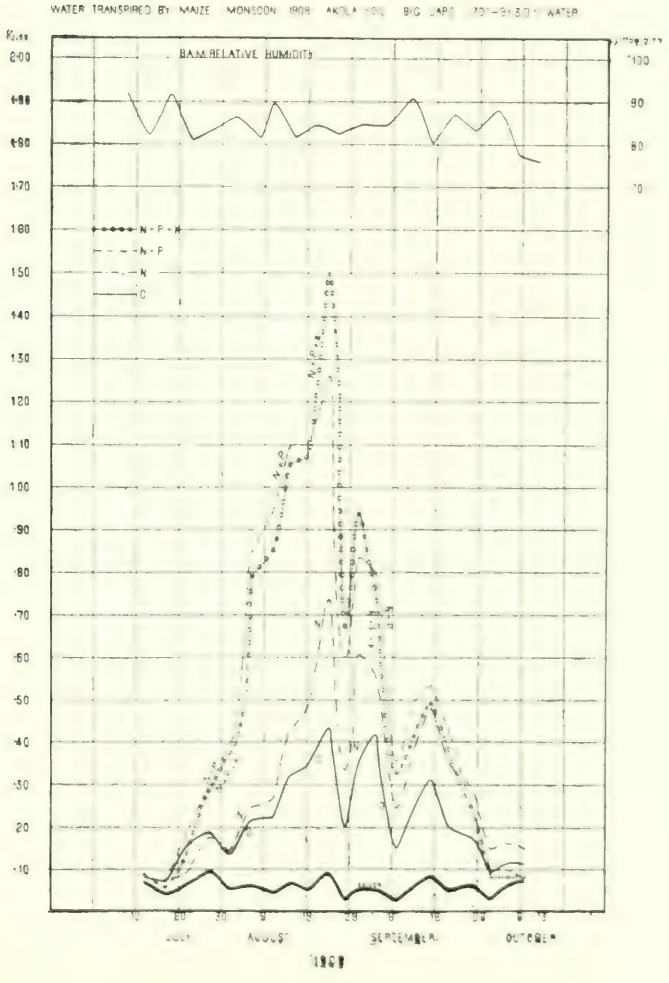
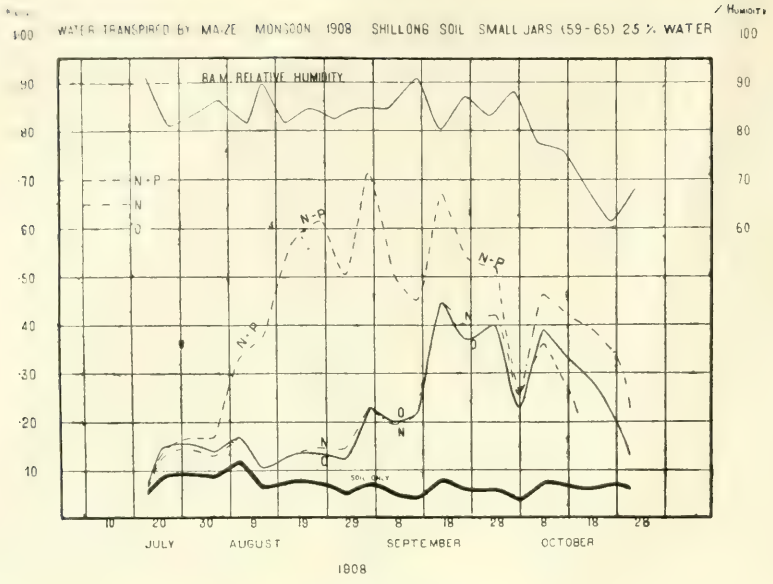


CHART I*d*.



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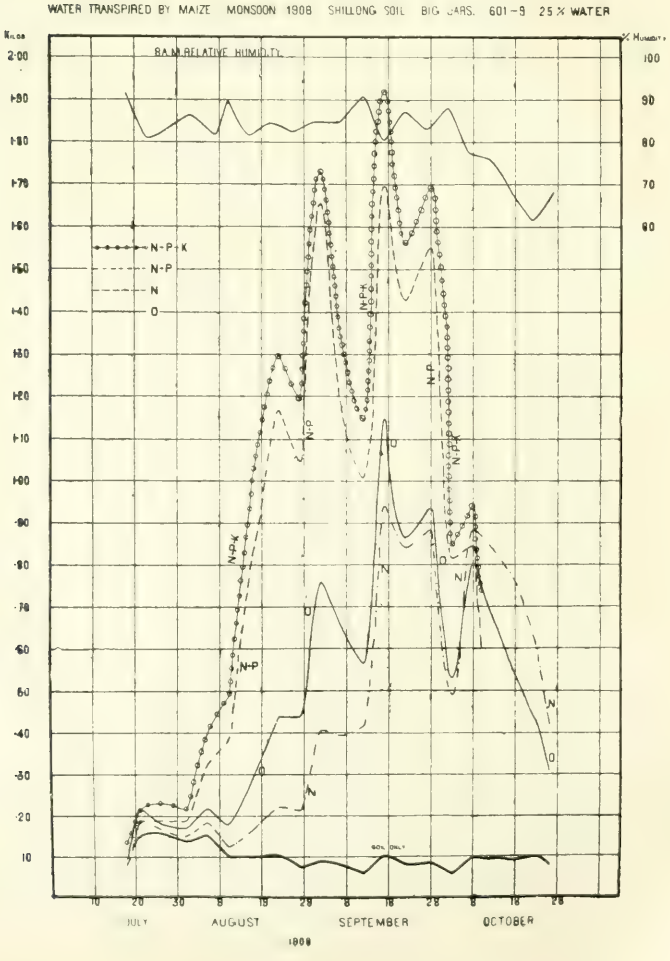


CHART II*a*.

WATER TRANSPIRED BY WHEAT—PUSA SOIL. 1909—10

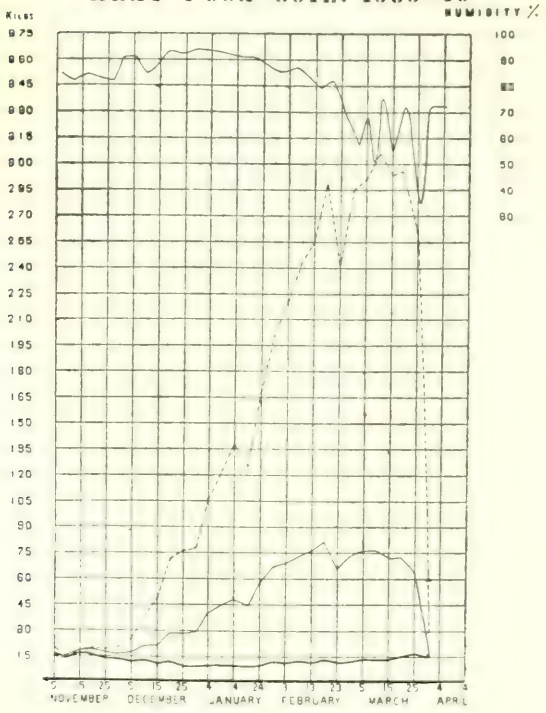


CHART II*b*.

WATER TRANSPIRED BY WHEAT—AKOLA SOIL. 1909—10

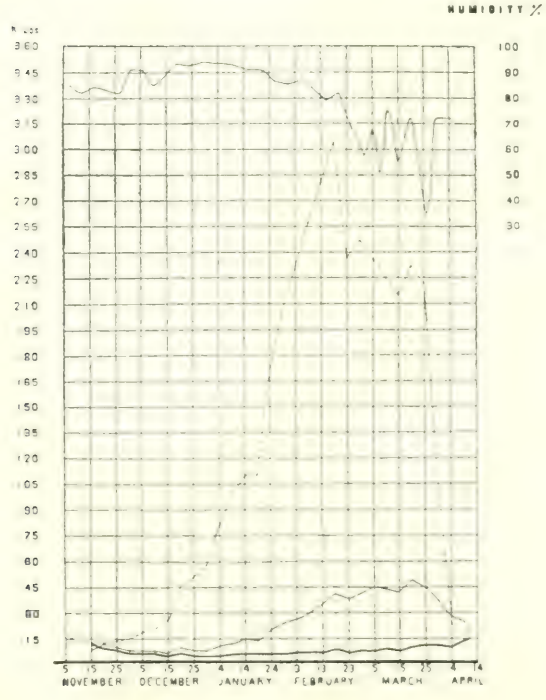


CHART III*a*.

WATER TRANSPIRED BY SARSON-PUSA SOIL. 1909-10

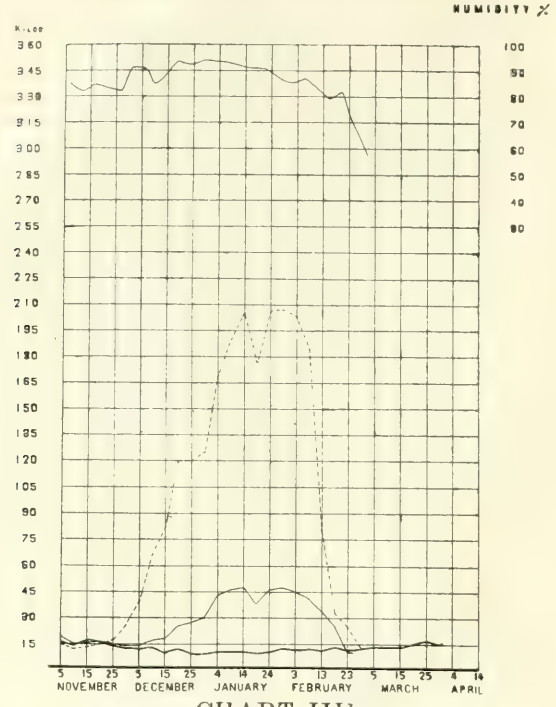


CHART III*b*.

WATER TRANSPIRED BY SARSON-AKOLA SOIL. 1909-10

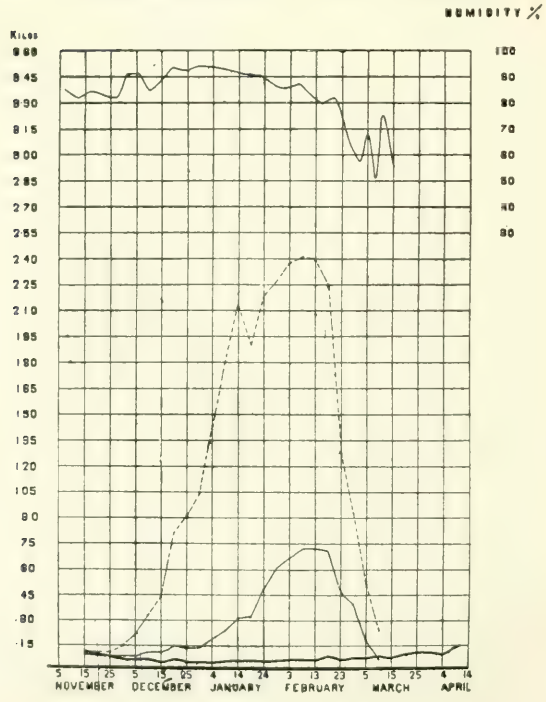


CHART IV*a*.

WATER TRANSPIRED BY LINSEED-PUSA SOIL. 1909-10

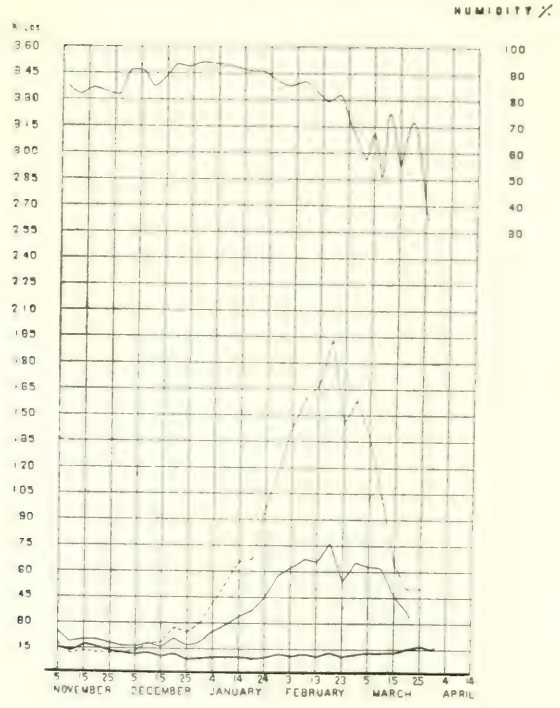


CHART IV*b*.

WATER TRANSPIRED BY LINSEED-AKOLA SOIL. 1909-10

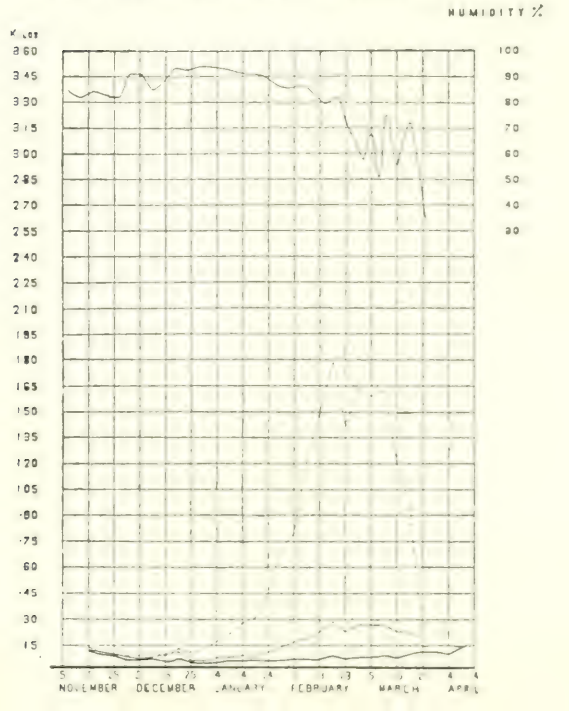


CHART V*a*.

WATER TRANSPIRED BY

BARLEY-PUSA SOIL. 1909-10.

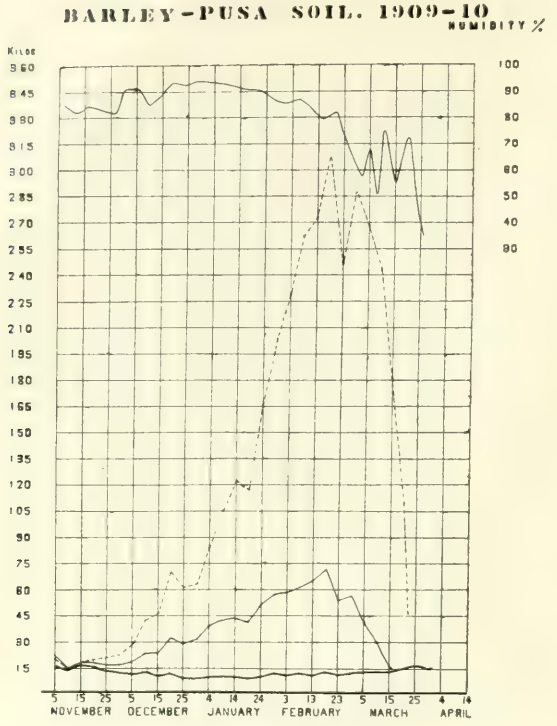


CHART V*b*.

WATER TRANSPIRED BY

OATS-PUSA SOIL. 1909-10.

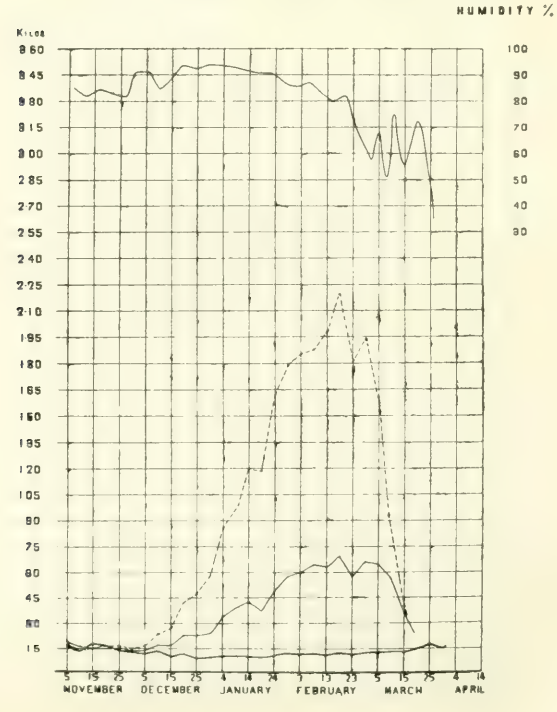


CHART V*c*.

WATER TRANSPIRED BY GRAM–PUSA SOIL. 1909–10

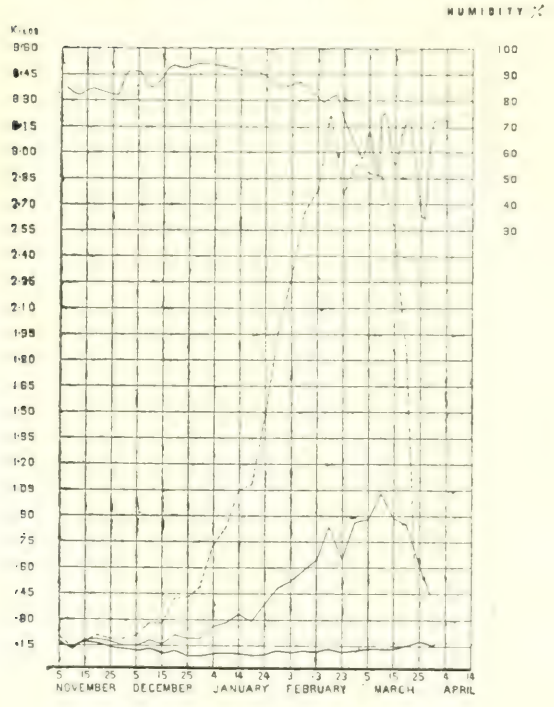


CHART V*d*.

WATER TRANSPIRED BY PEAS–PUSA SOIL. 1909–10

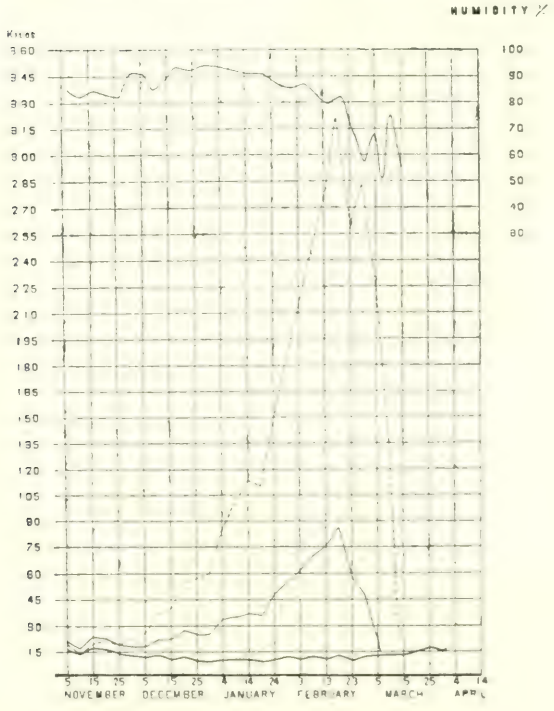


CHART IIc.

WATER TRANSPIRED BY WHEAT—SHILLONG SOIL. 1909–10

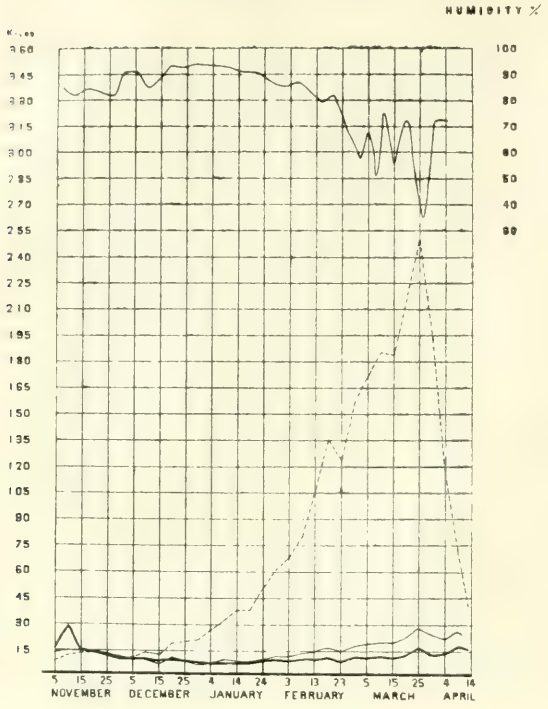
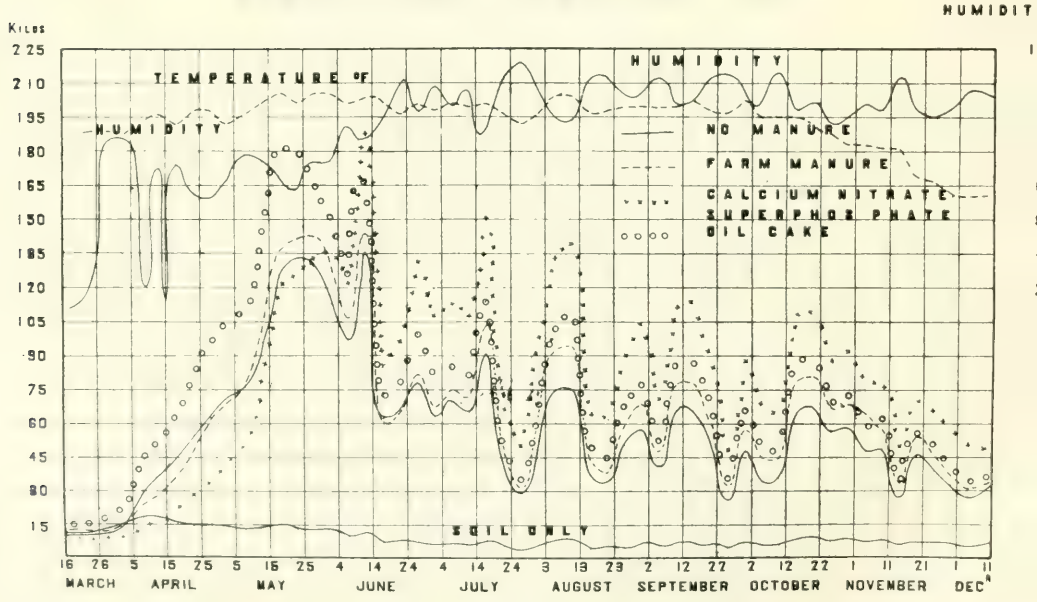


CHART VI.

WATER TRANSPIRED BY SUGAR CANE — PUSA SOIL — 1910



Deductions.

The effect of difference of Soil.—The most complete test of the effect of difference of soil on the transpiration ratio was with maize in 1908 when it was grown in four soils and in different sized jars. The results are collected in Statement No. I, and whether the comparison is made among the small jars or the large ones, it is evident that no marked effect is traceable to the chief variant, the soil. The unmanured plants in the Akola and Shillong soils provided a somewhat greater transpiration ratio than did those in Pusa and Palur soils, but if jar No. 703 Akola soil were excluded, the differences would be only nominal: and the similar comparison among the jars of manured soils shows correspondingly small variation. The second crop used was wheat (Statement II) grown in three soils all in large jars. Here the *unmanured* Akola soil led to a higher ratio than did either of the others, but no material difference was realised among the *manured* soils. Finally an examination of the ratios obtained for Sarson (Statement III) grown in two soils and for linseed, grown in the same two soils (Statement IV) also demonstrates how small is the effect of the soil on the transpiration. In all cases the chief factors are the nature of the plant and the effect of the manure.

The effect of the larger mass of Soil.—The effect of the mass of soil on the transpiration ratio was referred to in Memoir No. 8* when attention was drawn to the lower ratio which had usually been found when large jars of soil were employed. Hence a comparison of the ratios obtained for the seven "cold weather" crops which were grown in small jars of Pusa soil in 1908-09 with those grown in the large jars of the same soil in 1909-10 are of considerable interest. The means of the duplicates are as follows :—

* P. 167 and again p. 180

Crop.	1908-9. Small Jars.		1909-10. Large Jars.	
	No fertilizer.	Complete fertilizer.	No fertilizer.	Complete fertilizer.
Wheat ..	865	507	582	495
Barley	675	481	448	455
Oats	629*	551	493	388
Gram	1,429	977	1,216	660
Peas	835	530	811	595
Linseed	1,092	1,000	1,094	633
Sarson	736	624	481	384

These figures demonstrate very well the liability to obtain high ratios when the plants are only grown in small jars of soil ; and the effect is nearly as pronounced where fertilizers were used as where they were not. Accordingly the quantities of water estimated to be required as set out on page 182 of Memoir No. 8 need some revision, especially for linseed and gram and possibly guar. Linseed and gram undoubtedly have a higher transpiration ratio than the other cold weather crops named (see also p. 270 of this Memoir), but not so disproportionately higher as was first estimated. In other respects these newer tests support the several deductions which were made in the previous memoir.

Effect of Phosphates.—A special reference is necessary to the results obtained with the Palur soil. This soil was selected because it was known not to require phosphatic manure. The preceding pot-culture work in relation to transpiration had shown that where the fertilizers included superphosphate the transpiration ratio was small, and the question naturally arose whether this was due simply to a stimulating effect of the manure in a general sense or whether it was referable to a specific effect of phosphates. All other soils which had been used had produced a larger plant when superphosphate was added to the soil, showing that they were deficient in available phosphates, and coinciding with this increased growth was a decreased transpiration ratio. Transpiration records obtained with such soils were of no use for the elucidation of the foregoing question. If, however, a soil were employed which, so far as plant development is concerned, did not require

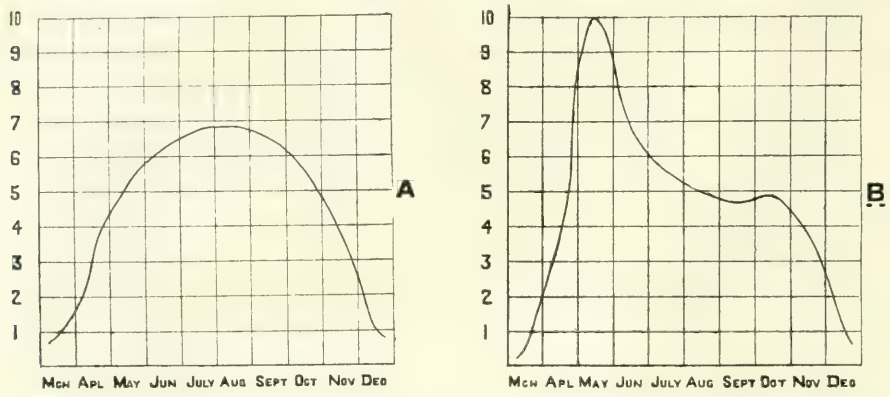
* Only one jar included ; other plants unusually small.

a phosphatic fertiliser, then if the superphosphate had any specific effect on transpiration, it might be expected to be demonstrated, in that without a marked increase of plant development, the transpiration ratio should be lowered. The Palur soil has fulfilled this office well, for the best plants and the lowest transpiration ratio were obtained by the use of a purely nitrogenous fertiliser, thus demonstrating that the effect of the superphosphate in the other experiments had been due purely to the deficiency in those soils of readily available phosphate and not to any specific action on transpiration by phosphates.

Sugar-cane.—The sugar-cane cultures deserve a special reference in part because of the importance of the crop, in part because the course of transpiration differed somewhat from that of most crops previously experimented with.

Two sets of "Ashy Mauritius" cane, one of the best types of thick cane, were planted in each of the jars early in March, all of which produced one or more shoots. In most jars either two or three canes developed well; the cane grew to a height of 9 or 10 ft. The canes were cut early in December, that is, after nine months' growth, and not only the fresh and dry weights ascertained but the juice also analysed. Reference to statement VI (*b*) gives details from which it is seen that the quality of the cane and juice left nothing to be desired. The juice was indeed some of the richest that I have ever met with. Turning next to the chart showing the daily transpiration, this includes the following curves (*i*) humidity, and temperature, a plain line and a dotted line respectively in the upper part of the chart, (*ii*) evaporation from soil only, (*iii*) four curves obtained from the cane jars. Of the fourteen jars, it was only convenient to record on the chart the curves of a small number, for the quantities of water transpired were so similar that the curves run together largely, and hence the mean daily water requirement is recorded on the chart for only the following (*a*) No manure, (*b*) Farm yard manure, (*c*) Calcium nitrate and superphosphate, (*d*) Oil-cake. The curves run together with remarkable uniformity, even small differences being present in all four. About 30 days after plant

ing, the canes shot rapidly and the maximum water requirement was reached after another 40 days. Thirty days later the requirement fell and throughout the remaining period of nearly six months the transpiration gradually fell off. It will be observed that herein lies a marked distinction. The curves for nearly all crops have been of the type (*a*) that for sugar-cane is of the type (*b*).



Although the four curves run parallel, those relating to the cane manured with oil-cake and with the artificial manure lie uniformly higher than those relating to the "Farm-manure" and "No manure" jars, which difference is largely, though not entirely, due to larger crops in the former cases. The period of maximum water requirement coincides apparently with three features; *namely*, a *combination* of (*i*) greatest heat and (*ii*) lowest humidity of the growing season, (*iii*) after the plants had commenced to grow rapidly. After the humidity rose to over 80 per cent. the water requirement fell materially. The effect of *humidity* is very clearly shown after June 15th, for with every rise of humidity there was a decrease of transpiration; with every fall an increased transpiration. The chart includes a curve of the shade temperature (.....line = °F) at 8 A.M., and there is generally with every rise of humidity a fall of temperature, so that both factors act together in the same direction on the transpiration. The effect of humidity is greater than that of temperature.

Referring now to Statement No. VI (*a*) it is seen that the weights of crop produced varied considerably according to the manure used. Farm manure either alone or mixed with

superphosphate caused a moderate increase: oil-cake was more effective, and oil-cake and superphosphate more effective still. Calcium nitrate alone was about equal to farm manure, but calcium nitrate plus superphosphate produced a very much larger crop than any of the other fertilisers, in fact, it nearly trebled the yield in comparison with the unmanured plants. At the same time too much weight should not be attached to these manurial effects. It is to be recollected that both farm manure and oil-cake must undergo changes, due to bacterial action, before they become plant foods, and we know nothing about the precise bacterial conditions in this experiment. On the other hand, the value of the mixture of calcium nitrate and superphosphate is as distinctly demonstrated in these cultures as it has been regularly throughout this work.

Lastly, from Statement VI (*a*), we learn what the relative water requirement of the sugar-cane crop is. This is shown in the last column; the transpiration ratio varies from 470 for the unmanured cane down to about 200 for the cane manured with the artificials These ratios are, on the whole, the lowest that I have met with throughout the series of experiments on transpiration, and demonstrate that, relatively to the weight of crop grown, the water requirement of sugar-cane is very small. The weight of a good cane crop is, however, very large: 30,000 lbs. of cane per acre is very common: 60,000 is in certain localities regularly obtained; add to these the weights of leaves which will be 50 per cent. more. Such crops are equivalent to something like 25,000 and 50,000 lbs. of dry matter per acre; and the equivalent in water, assuming the ratio to be 300, works out to 33″ and 66″ respectively. Such brief calculations will be sufficient to explain the chief reason for the liberal irrigation which the cane crop requires in the dry parts of India. It is also to be recollected that the transpiration ratios have been obtained in a country (Behar) which enjoys a comparatively humid climate, and since the effect of humidity on transpiration is so marked, the ratio for the drier parts of India such as the Punjab or Sind, may be higher.

PART II.

Field Experiments.

In 1907 it was decided to trace the changes which would occur in the moisture content of a soil where a crop is growing, in order (*i*) to compare such changes of concentration with those of fallow soil, and (*ii*) to try to calculate the transpiration ratio from these changes. There are probably no records of soil-moisture taken throughout the root range of a crop over the whole growing period, and hence the comparison indicated under (*i*) would, in any case, be of considerable interest; and if moreover such records could be utilised to check even approximately the transpiration ratios of crops which were being obtained by the pot-culture methods, the value of the work would be very greatly increased.

It will perhaps enable the reader to appreciate the general conditions associated with the *method* which has been employed in this work if the following matters are explained :—

(*i*) The method of obtaining specimens of soil and of estimating the amount of water present in them down to a number of feet from the surface has been described in Memoir No. 6, and it will be sufficient to say here that an iron or steel cylinder 2″ diameter and 3″ or 6″ long, attached to an iron shaft, is forced by revolving the shaft handle and with the aid of a lever (see plate No. I) into the ground until it has sunk to the desired depth, *i.e.*, 3″ or 6″ respectively, and then withdrawn; if the soil is not absolutely dry or not excessively wet, the cylinder brings with it the small column of soil which is required. The cylinder is then detached from the shaft, weighed, and the soil then transferred to a suitable tray in which it is dried at about 100°C. By thus taking out successive cylinders full, specimens of the soil of consecutive depths, 3″ or 6″, are readily obtained, and thus the moisture determined in successive depths of the soil. Moreover, since the *volume* of soil removed in each cylinder is readily calculated, the amount of water present can be expressed in terms of weight per unit

volume; "pounds per cub. feet" has been adopted at Pusa. The cylinders which were previously described are cylindrical inside and slightly conical in the lower part outside: (see plate No. I), *i.e.*, they force the soil away from them and withdraw a cylinder of soil of their internal dimensions. Whilst these cylinders work perfectly well in moist soil, they do not cut into a dry soil freely, and it became necessary to devise one which would do this. The pattern adopted is shown in the plate. It consists of a plain cylinder, *i.e.*, it is cylindrical on *both* faces; it is about 1″ longer than the depth it is required to penetrate, and is 1/8″ thick. On its lower edge two tongues of the metal protrude and each of these tongues is cut into three parts, the centre one of which is then bent *inwards* slightly. When this cylinder is used, the teeth *disturb* the soil they come in contact with, and this disturbed soil passes into the cylinder; consequently the amount of soil abstracted is equal to the *outer* dimension of the tool. This tool works very well in dry soil and cuts through *kankar* (concretionary limestone) readily.

The moisture record has been maintained to a depth of 9 ft. in most of the work.

It is quite necessary to record with considerable precision exactly where each boring is made in the plot. After completing a boring the hole is filled most conveniently with dry earth: this earth will naturally abstract moisture from the soil surrounding it, and hence a subsequent test should not be made within a certain radius of a previous one; this radius works out to about 1′ 4″ in order to avoid a possible error of ·1 lb per cub. ft. In order then to be able to trace the position of boreholes, reliance has been placed on rectangular measurements from a fixed point, and two sides of the area of land comprising the plot or series of plots, which was considered much safer than indicating boreholes by any direct means such as by pegs.

(*ii*) In the first season the moisture was determined before sowing the crop, but in subsequent years this has been also done after the plant was well above ground. In order to ascertain the amount of water with as much precision as possible, it

should be determined in each plot; but when these aggregated thirteen, and since only one test (which included eighteen 6″ specimens to be bored out and dried) could be carried out per day, it became practically impossible to test each plot at the time of sowing. In 1908 four such tests were made, each representing the moisture of three plots at sowing time, but it was decided to try to make these tests somewhat later, after the crop had commenced to grow, one in each plot. In order to do this bricks were laid between rows of plants (see plate II) on which a platform was laid over the young crop, and the soil specimens were thus obtained without injury to the crop. A further advantage lies in making the initial moisture determination at this period rather than at sowing time, inasmuch as it is only after the plant is a few inches high that it commences to transpire more than nominal amounts of water, and it is from this period rather than from date of sowing that many of the estimates of water have been made.

(*iii*) The manner of expressing the quantities of water involved needs a word of explanation. It has been mentioned that, from the water found in the soil specimens, the weight of water per unit volume of soil is readily calculated, and that this is expressed in terms of "pounds per c. ft." But whilst this mode of expressing the "concentration" of the water enables one to measure changes in that respect throughout the 9 ft. of soil in which the records have been kept, it does not enable one directly to compare quantities of water with the area of the land or weight of the crop. For this purpose it becomes necessary to calculate from the ascertained concentrations, the weight of water in the soil, say, throughout the root range of a unit area, and to express the result in terms such as lbs. or tons of water per acre x feet deep.

We must in fact adopt a *column of soil* of a specified cross section. For the purposes of the work now being described the unit adopted is a soil column 9 ft. deep and 1 sq. ft. cross section. *The depth* 9 ft. was initially selected because the shaft of the boring tool did not admit of specimens of soil being taken to a

PLATE I.

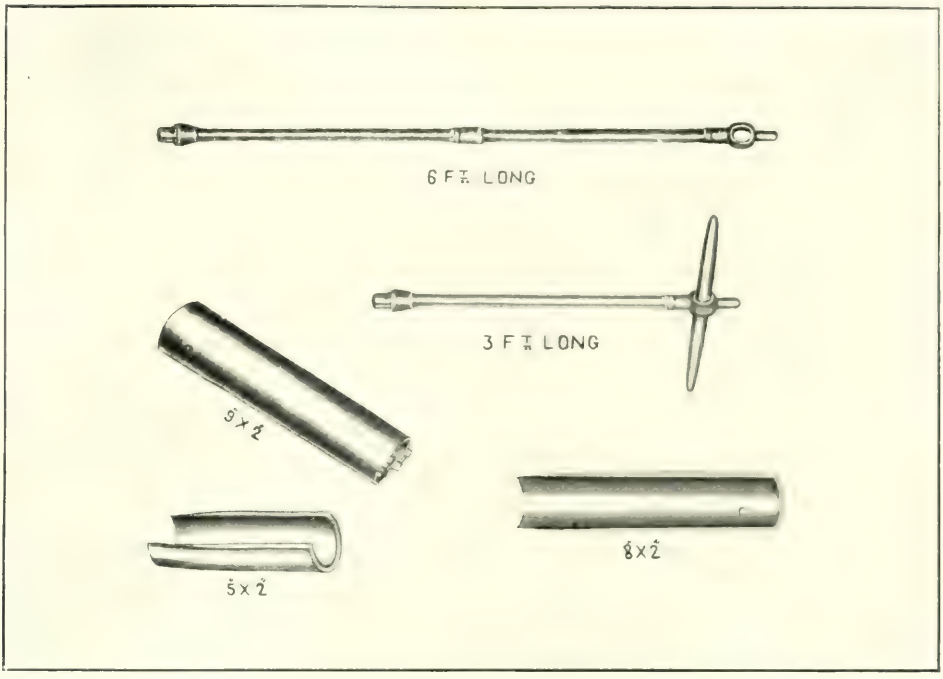


PLATE II.

greater depth. It was also believed that changes of concentration of water due to plants would not extend in the soils which were selected for experiment beyond this depth: and although experience has indicated a somewhat greater depth to be affected at Cawnpore, 9 ft. has proved to be substantially sufficient. A longer shaft could readily have been provided, but the work had proceeded very far before any advantage in taking deeper lying soil specimens was observed: an advantage which would indeed have been only nominal. Also it may be mentioned that, taking these specimens and executing all the weighments in the hot weather is no light task, especially when deep borings are taken. Then, secondly, a small *unit cross section* was selected because the moisture record is obtained from either one or at most two borings of only 2″ diameter each. To quote the weight of water involved as (say) "tons per acre" would bear no relationship to the actual mass of soil experimented with. A small unit was hence advisable, and the one adopted is a very convenient one. The weight of water (pounds) in the unit column 9 ft. × 1 sq. ft. may also be converted to inches of water on the land surface if divided by 5·21, since this is the weight (pounds) of water 1″ deep × 1 sq. ft. Then, again, it became necessary to connect the weight of water in the soil column with the crop, and here also a small unit of area is very desirable. Our moisture determinations were made in only very small columns, 2″ diameter of soil, and although by making two such tests 2 or 3 ft. apart, a comparatively accurate estimate of a much larger area is obtained, it is to be recollected that these tests only yield information of the amount of water within a small area, for it is known that the quantity of water present in any field varies almost from yard to yard to such an extent that these differences may affect quite seriously the calculations which are necessary in this work. Theoretically one would like to estimate the crop grown on the actual small soil column in which the moisture is determined. Such would be obviously impossible, but sufficient has been said to explain why a quite small area of crop has been selected for weighment. It is the more necessary to go into these

details because in much agricultural work the weight of a crop from not less than at least 1/10 acre is considered necessary in order to obtain useful data. In this soil moisture work, however, had such an area been weighed, most of the crop would have been drawing its moisture supply from an area, or volume of soil, in regard to which the moisture record had but a slight connection. At the same time it is highly probable that had only (say) the crop on 1 sq. ft. been weighed, an even greater error in measurement would have occurred; for whilst one could measure fairly accurately 12″ from between one row of plants to another corresponding line, the similar measurement *in* the row would have led to difficulties as to whether a certain plant should be included or not in the 12″. Accordingly it was necessary to cut the crop from an area so large that such errors would become negligible, and for much of the work the crop has been cut from about 50 or 60 sq. ft. Such an area is large enough for the purpose, whilst it is not so large that the various measurements of soil moisture have not a close relationship to it. If then an imaginary column of soil be pictured 9 ft. high and 1 sq. ft. cross section with the crop on the top of it, the quantities of water which we shall deal with will be readily appreciated.

(*iv*) It will probably be at once apparent that such work as we are considering would lead to but little useful result if conducted during very wet weather. *All* additions of water at the surface are not inadmissible. For instance, not only can small rainfalls be readily accounted for, but as will be seen, successful measurements have been made where irrigation has been applied to the crop. The condition which in fact limits such additions of water is that these shall be measurable in the soil. If they are so great that drainage occurs throughout the root range and below it, then, since we have in the field no means of measuring the amount of such drainage, soil moisture records would only serve to show changes of water concentration, and these would be of little value by themselves under such conditions. Hence no attempt has been made to conduct these measurements during the monsoon period, which is usually

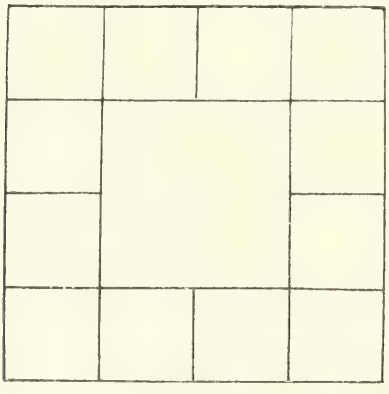
characterised by a rainfall which not only suffices for a growing crop but is in excess of this and provides water which drains away below. The experiments have on this account been necessarily restricted to the "cold weather" period when the rainfall is only nominal.

Plan of the experiments.—The first experiment was made in the cold weather of 1907-08 when oats were sown on one-half of a small plot, the other half being left fallow. The data obtained were of such interest that it was decided to extend the scope of the investigation, and for the following season plots of land were prepared (*i*) at Pusa for six crops to be grown on manured and on unmanured land, and (*ii*) at Cawnpore for six crops similarly on manured and unmanured soil. In addition, records were maintained at Cawnpore for some plots of irrigated wheat, in which measured quantities of water are used annually for this crop. Thirdly, in the season 1909-10, this work was repeated ; at Pusa on two different soils ; at Cawnpore on contiguous plots to those used in 1908-09.

These experiments have not been made without meeting with difficulties. The monsoon of 1908 was an exceptionally weak one, and the land at Pusa was in October of that year so dry at the surface that germination was imperfect in many fields ; thus, after sowing our first selected plots, these had to be abandoned and others of a more clayey character substituted. Here germination was good on some plots and sufficiently so on the others to yield a uniform, if only a moderate crop. At Cawnpore in that season, likewise after a weak monsoon, the weights of crops were small ; in such cases the effect of the experimental error is necessarily magnified and for this reason the whole unirrigated series was discarded. On the other hand, the irrigated wheat grew naturally to great perfection, and to the satisfaction of Mr. Burt and myself it was found that the moisture record could trace the depth to which the irrigation water descended into the soil. Moreover an examination of the data obtained, proved perfectly serviceable in accounting for the irrigation water and connecting the total decrease of water in the soil with the crop.

In 1909 it was decided to repeat the experiment on two classes of land at Pusa, the one a stiff clay and the other a lighter soil. But the monsoon was so unusually heavy that both these fields were too wet at autumn sowing time to admit of their use, for it was feared that drainage had not then ceased in the subsoil which would have necessarily interfered with the record. Accordingly two other sets of plots had to be selected, and of these one was a lighter class of land than that utilised in 1908-09, whilst the other was in still lighter land. Germination and subsequent growth were all that could be desired, but rats got into both sets of plots when the crops were at their best and the whole of those on the lighter land had to be abandoned : of those on the somewhat heavier soil (the one first mentioned above), portions of five were intact at harvest and these have yielded useful data. At Cawnpore the yields of *unirrigated* crops were again small, and it is intended to repeat this series : the irrigated wheat crop was, as previously, a very good one and again yielded valuable information.

The procedure adopted may now be concisely stated. The land selected is left fallow during the monsoon, and is thus at the end of October in the most favourable condition as regards moisture for the "cold weather" crops which are sown at this period. The cultivation should be the very best and most uniform possible. The plots are then marked out. The accompanying woodcut



represents those at Pusa in 1909-10 and the others were similar. Determinations of soil moisture at one or two points are now made so as to form an estimate of what this is at sowing time, though, as has been explained, another and more complete test is taken at a later date for the "initial" moisture. When sowing, lines to receive the seeds, of suitable depth and distance apart, are opened in the plot and into each a

weighed quantity of seed is dibbled by hand with as great uniformity as possible, the aim being to have the plants distributed so evenly that anything in the nature of "bunches" of plants here and there is avoided. For the same reason cultivation of such plots with cattle is not advisable, for it is almost impossible to avoid adventitious manuring by them. After the plant is some few inches high, a determination of moisture is made in the manner already described (p. 236) at a point in each plot which appears likely to prove the most *uniform* (not necessarily the heaviest). Weeds are constantly removed so long as this can be done without injury. The crop is then left to develop and ripen off. At harvest about 50 sq. ft. of the most uniform part of the crop, and which should include in its area the site of the initial moisture determination, is cut, air-dried, weighed, threshed, and moisture determinations made in the several parts so as to be able to compute the weight of dry matter in the whole. Moisture determinations are also made within the harvested area, and since all crops do not mature at the same time, there is now rather more time available, and the moisture is determined at *two* points within the area ; the one is taken between two rows of plants, the other exactly where a plant grew. It is the more necessary to duplicate the estimation of soil moisture at harvest because, whilst at sowing time the moisture is very evenly distributed throughout the small area involved, at harvest the uniformity of the remaining moisture will depend largely on the uniformity of the crop and there is necessarily more *liability* to variation in its distribution. Again a month or six weeks after harvest a further estimate of the moisture has been taken in a number of the plots in order to ascertain what changes take place in its quantity. Periodically during the season determinations of the moisture in the fallow plot are also made.

The rainfall of the several seasons at the two agricultural stations will be of interest, and is here stated. It is seen that at both stations the rainfall during the growing period was quite small, and that the crops had to depend almost entirely on the

soil moisture or, as at Cawnpore, on this plus irrigation for their supply of water.

STATEMENT No. VII.

Pusa.								Cawnpore.			
1907-08.		1908-09.		1909-10.		1908-09.		1909-10.	
	In.		In.		In.		In.		In.
Jan. 12 ...	·44	Dec. 25 ...	·04	Dec. 21 ...	·12	Jan. 4 .	·08	Dec. 25 ...	·11
,, 31 ...	·03	Jan. 18 ..	·06	Jan. 18 ...	·01	,, 11 .	·01	,, 26 ...	1·64
Feb. 1 ...	·54	,, 28 ..	·05	Feb 18 .	·02	,, 14 ...	·11	Jany. 2 ...	·06
,, 2 ...	·84	Feb. 17 ...	·01	Mar. 4	·01	Feb., 24 ...	·05		
,, 3 ...	·01	,, 21 ...	·16	,, 10 ...	·06	April 20 ..	·52		
,, 6 ...	·01	,, 24 ...	·05	April 29 ..	·13	,, 21 ...	·63		
,, 28 .	·11	,, 25 ...	·01	,, 30 ...	·01	,, 22 ...	·19		
,, 29 ...	·76	April 13 ..	·07			,, 23 ...	·88		
Mar. 1 ...	·10	,, 15 ...	·38						
,, 12 ...	·005	,, 18 ...	1·15						
May 7 ...	·53	,, 19 ...	·71						
		,, 24 .	·01						
		,, 25 ..	·15						
		,, 26 ...	·05						
		,, 28 ...	·01						
		,, 29 ...	·91						

Rainfall for each crop.

Crop.	Pusa.			Cawnpore.	
	1907-08.	1908-09.	1909-10.	1908-09.	1909-10.
	Inch.	Inch.	Inch.	Inch.	Inch.
Oats	2·74	·38	·22	...	
Wheat	..	·38	·22	·25	1·81
Barley		·38	..	..	.
Peas	.	·38	...	..	
Linseed	.	·38	·22	..	...
Mustard	...	·32	·16	...	..

Discussion of the data obtained.

Change of concentration of water.—The data relating to the three years' work are set out in Statements Nos. VIII to XX and in charts which are numbered VIII and XIII to XVIII. This numbering of the charts has been adopted for simplicity of reference; the chart number corresponds with that of the statement from which it is derived.

The Experiments at Pusa.—Directing attention firstly to the data relating to the oat crop grown at Pusa in 1907-08 (State-

ment VIII and Chart No. VIII) it will be seen that in the *fallow* soil the water decreased to a greater degree in the stratum 1′ 9″ to 3′ 0″ than in the soil *above* it. This feature is quite characteristic of the soil of this part of the field and was observed also in the previous year. The soil is much more sandy in the third and part of the fourth foot than in the first two feet; below 4′ 0″ the soil is much more clayey. So likewise where the oat crop grew, there is a distinctly greater decrease of water content in the more sandy stratum than just above it. Then, secondly, there is a considerably greater decrease of moisture, both in the fallow soil, as also where the oats grew, in the first five feet than below this depth; the effect of the oat crop being of the two much more pronounced. Thirdly, whilst in the fallow soil there is a decrease down to about 7 ft.: this decrease extends where the oats grew to 9 ft. Now these features are very generally brought out by the data relating to the several crops grown in the two subsequent seasons, and variations among themselves depend on three factors, which are (*i*) the nature of the soil, (*ii*) the nature of the crop, and (*iii*) the weight of the latter. Of these the last has exerted generally the greatest influence, though the nature of the crop is nearly as effective. It will also be observed that the crops of 1908-09 caused a marked decrease down to about 7′ or 7′ 6″, those of 1909-10 down to 7′ 6″ or 8′ 0″, that is, rather deeper, though the difference is not great. The soils are different only in degree, that employed in 1908-09 being a stiffer soil than that of 1909-10; the amount of water present per unit column was, in the former, at sowing time considerably less than in the latter. It will be recollected that this is readily accounted for by the difference of the preceding monsoons, the rainfall of 1908 having been about one-half the normal, that of 1909 about twice the normal. Hence the question naturally occurs whether the crops in 1908-09 had not to take water from a greater depth in that soil than they would have done, when, after a normal monsoon, the soil would have contained more water: the corresponding question in regard to the experiments of 1909-10 hardly arises, because although the monsoon of 1909

had been so heavy, drainage had ceased in the first 9 ft. before sowing time, and this soil would have contained at sowing time after an ordinary monsoon rainfall as much as it did on the occasion of the experiments. Another feature which is regularly present is that there was but little decrease of concentration of water at 9 ft. in any of the experiments.

The Experiments at Cawnpore. The character of the soil.— The Cawnpore soil differs chemically from that at Pusa only in possessing an ordinary proportion of lime. Otherwise it consists of very fine earth, but is probably somewhat more clayey. In this land irregular beds occur containing nodules of concretionary limestone (*kankar*). The effect of dry weather on this soil when fallow is illustrated by the Chart No. XXV from which it is seen that it dries much more at the surface than the Pusa soil does, but that the drying effect does not extend nearly so deep. It has been mentioned that unirrigated crops do badly in this soil in the absence of rain, but with moderate irrigation they do well.

The data relating to these irrigation experiments, *vide* Statements XIX, XX, exhibit the same general features as those at Pusa, but here the decrease of water concentration is perceptible to even a greater depth and the test down to 9′ 0″ does not exhibit quite the whole extent of the decrease where the crop grew.

STATEMENT No. VIII.

OATS, PUSA, 1907-8.

Exhibiting the amount of water present in the soil (a) *where fallow.* (b) *where Oat crop was grown,* 1907-8, *pounds per cub. ft.*

Depth, ft.	FALLOW LAND.			OAT LAND.		
	Initial moisture, 8th Nov. 1907.	31st March 1908.	4th May 1908.	Harvest, 31st March 1908.	6th May 1908.	22nd May 1908.
0 – ¼	14·6	6·8	4·5	·5	·5	·7
¼ – ½		11·0	7·8	1·8	·7	1·5
½ – ¾	14·4	10·9	8·9	2·6	1·7	2·8
¾ – 1		11·7	10·6	3·8	3·1	4·2
1 – 1¼	13·1	11·8	8·0	4·0	4·2	4·2
1¼ – 1½		11·7	9·7	4·3	4·3	4·6
1½ – 1¾	11·6	11·3	10·5	3·9	3·4	3·8
1¾ – 2		8·6	8·9	3·0	3·0	3·0
2 – 2½	12·4	7·3	7·4	2·3	2·3	3·2
2½ – 3	15·9	16·3	9·7	2·9	3·5	4·5
3 – 3½	18·9	12·5	11·7	3·8	5·6	5·7
3½ – 4	18·3	12·2	9·4	4·3	7·0	5·8
4 – 4½	19·5	14·6	11·8	6·6	10·8	14·3
4½ – 5	23·0	18·8	20·0	14·3	16·7	14·3
5 – 5½	23·4	—	...	...	...	...
5½ – 6	24·0	20·0	19·8	15·7	16·9	18·6
6 – 6½	24·3	—	...	...	...	...
6½ – 7	24·7	24·2	23·4	18·4	20·0	21·1
7 – 7½	24·9	—	...	...	...	...
7½ – 8	25·1	25·8	25·3	23·3	24·1	23·6
8 – 8½	25·4	—	...	...	...	...
8½ – 9	26·5	26·8	25·5	26·5	25·8	24·7

Dry matter per sq. ft. ... ·186 lbs.

LBS. WATER IN UNIT COLUMN.

Initial	180·0	
Rain=2·8″	14·8	
	194·8	
Direct evaporation ...	14·0	
Remaining at harvest	104·3	
Transpired	76·5	
	194·8	
Ratio	76·5 / ·186	= 411

STATEMENT No. IX.

Wheat, Pusa, 1908-09.

Depth ft.	Pounds of Water in Soil per Cub. Ft.	
	Manured.	
	Initial, 11th December 1908.	Harvest, 30th March 1909.
0 — ½	12·9	1·9
½—1	18·2	4·9
1 —1½	18 7	6·7
1½—2	20 8	8·9
2 —2½	18·4	10·0
2½—3	21·3	13·3
3 —3½	15·2	9·8
3½—4	19·7	14·5
4 —4½	18·3	10·7
4½—5	16·6	11·4
5 —5½	16·0	12·2
5½—6	15·3	12·7
6 —6½	13·7	11·4
6½—7	12·1	8·2
7 —7½	15·5	12·8
7½—8	18 9	18·6
8 —8½	20·4	19·9
8½—9	20·4	20·3

Sown		November 5th, 1908.
Harvested		March 30th, 1909.
Area of crop which was weighed		52·2 sq. ft.
Weight of dry matter	Seed	1·86 lbs.
	Straw, &c.	3·32 lbs.
	Total ..	5·18 lbs.
Dry matter per sq. ft.		·099 lbs.

Lbs. water in unit column.

Initial	156·2
Rain = ·38″	2·0
	158·2
Direct evaporation	11·5
Remaining at harvest	105·6
Transpired	41·1
	158·2

Ratio . . ... $\frac{41{\cdot}1}{{\cdot}099} = 415$

STATEMENT No. X.

BARLEY. PUSA. 1908-09.

Depth ft.	Pounds of Water in Soil per Cub. Ft.			
	Manured.		Unmanured.	
	Initial, 12-12-08.	Harvest, 21-3-09.	Initial, 18-12-08.	Harvest, 27-3-09.
0 — ½	9·7	1·6	8·5	1·2
½—1	16·8	5·2	14·3	4·4
1 —1½	17·2	7·2	16·4	6·5
1½—2	19·2	9·0	18·4	8·0
2 —2½	19·8	10·4	20·2	10·6
2½—3	22·5	13·7	20·5	15·1
3 —3½	19·1	12·5	24·9	15·5
3½—4	16·0	10·8	22·1	15·2
4 —4½	20·3	11·1	19·3	13·8
4½—5	13·4	12·6	18·5	12·1
5 —5½	13·9	11·4	17·0	11·0
5½—6	14·3	12·0	15·5	11·5
6 —6½	13·1	11·9	13·6	10·5
6½—7	12·0	10·6	11·8	10·6
7 —7½	15·1	11·2	17·1	10·5
7½—8	18·3	17·2	22·4	18·2
8 —8½	20·7	19·3	22·3	19·1
8½—9	20·2	20·2	21·1	20·6

Sown	... November 3rd, 1908	... November 3rd, 1908.	
Harvested	... March 21st, 1909	... March 27th, 1909.	
Area of crop which was weighed	...	50·75 sq. ft.	32·6 sq. ft.
Weight of dry matter ...	Seed	2·93 lbs.	1·62 lbs.
	Straw, &c.	2·67 lbs.	1·80 lbs.
	Total ...	5·60 lbs.	3·42 lbs.
Dry matter per sq. ft.	...	·11 lbs.	·105 lbs.

Lbs. water in unit column.

Initial	150·9	161·9
Rain = ·38"	2·0	2·0
	152·9	163·9
Direct evaporation ...	11·5	11·5
Remaining at harvest	103·9	107·2
Transpired	37·5	45·2
	152·9	163·9
Ratio	37·5 / ·110 = 341	45·2 / ·105 = 430

STATEMENT No. XI.

Oats, Pusa. 1908-9.

Pounds of Water in Soil per Cub. Ft.

Depth ft.	Manured.		Unmanured.	
	Initial, 10-12-08.	Harvest, 10-3-09.	Initial, 10-12-08.	Harvest, 11-3-09.
0 — ½	12·1	2·2	8·5	1·9
½ — 1	16·3	4·7	14·3	6·0
1 — 1½	16·5	5·9	16·5	7·1
1½ — 2	20·8	7·9	18·4	10·7
2 — 2½	19·5	13·8	20·2	9·2
2½ — 3	18·2	11·3	20·5	17·1
3 — 3½	18·4	13·0	24·9	17·2
3½ — 4	16·0	14·9	22·1	13·6
4 — 4½	15·5	8·8	19·3	14·7
4½ — 5	19·4	17·8	18·5	13·2
5 — 5½	17·7	13·8	17·0	11·8
5½ — 6	16·2	14·7	15·5	12·0
6 — 6½	17·1	11·5	13·6	12·2
6½ — 7	18·0	10·2	11·8	10·8
7 — 7½	19·0	17·6	17·1	15·1
7½ — 8	20·1	20·5	22·4	19·7
8 — 8½	19·8	19·9	22·3	18·8
8½ — 9	20·4	22·2	21·1	21·1

		Manured.	Unmanured.
Sown		November 3rd, 1908.	November 3rd, 1908.
Harvested		March 10th, 1909.	March 11th, 1909.
Area of crop which was weighed		55·8 sq. ft.	66·64 sq. ft.
Weight of dry matter	grain	3·57 lbs.	3·35 lbs.
	straw, &c.	5·14 lbs.	3·95 lbs.
	Total	8·71 lbs.	7·30 lbs.
Dry matter per sq. ft.		·156 lbs.	·110 lbs.

Lbs. water in unit column.

	Manured.	Unmanured.
Initial	160·5	162·0
Rain = ·38″	2·0	2·0
	162·5	164·0
Direct evaporation	11·5	11·5
Remaining at harvest	115·3	116·1
Transpired	35·7	36·4
	162·5	164·0
Ratio	$\frac{35·7}{·156}$ = 230	$\frac{36·4}{·110}$ = 331

STATEMENT No. XII.

Linseed, Pusa, 1908-09.

Pounds of Water in Soil per Cub. Ft.

Depth. ft.	Manured.		Unmanured.	
	Initial, 13-12-08.	Harvest, 16-3-09.	Initial, 15-12-08.	Harvest, 17-3-09.
0 - ½	15·4	2·7	12·6	2·8
½—1	17·8	6·0	15·7	6·7
1 —1½	19·7	6·1	17·3	7·1
1½—2	19·9	6·8	17·9	7·5
2 —2½	20·1	8·0	18·0	9·4
2½—3	19·8	8·0	21·4	11·1
3 —3½	18·4	9·9	21·0	10·3
3½—4	22·7	13·0	16·1	9·5
4 —4½	15·9	10·7	15·1	6·9
4½—5	16·3	12·7	16·8	12·3
5 —5½	17·0	12·8	16·7	12·6
5½—6	17·7	13·5	16·6	12·2
6 —6½	17·9	13·3	15·1	11·1
6½—7	18·2	13·3	13·6	11·6
7 —7½	19·3	18·2	17·0	19·1
7½—8	20·5	20·4	20·5	19·8
8 - 8½	21·0	19·5	21·4	20·4
8½—9	19·6	20·3	19·9	21·5

Sown	...	November 3rd, 1908.	November 3rd, 1908.
Harvested	...	March 16th, 1909.	March 17th, 1909.
Area of crop which was weighed	...	... 51·3 sq. ft.	48·12 sq. ft.
Weight of dry matter	Grain ...	1·26 lbs.	1·02 lbs.
	Straw	2·39 lbs.	1·82 lbs.
	Total ...	3·65 lbs.	2·84 lbs.
Dry matter per sq. ft.		·071 lbs.	·059 lbs.

Lbs. water in unit column.

Initial	...	... 168·6	156·3
Rain ·38"	...	2·0	2·0
		170·6	158·3
Direct evaporation		11·5	11·5
Remaining at harvest		108·1	105·9
Transpired		51·0	40·9
		170·6	158·3
Ratio		$\frac{51·0}{·071}$ = 718	$\frac{40·9}{·059}$ = 693

STATEMENT No. XIII.

Mustard, Pusa, 1908-9.

Depth, ft.	Pounds of Water in Soil per Cub. Ft.				
	Manured.		16-4-09.	Unmanured.	
	Initial, 8-12-08.	Harvest, 22-2-09.		Initial, 14-12-08.	Harvest, 2-3-09.
0 — ½	15·5	6·7	5·4	12·9	4·3
½—1	18·6	10·2	9·6	14·7	7·3
1 —1½	20·5	11·9	11·0	17·6	8·5
1½—2	20·5	11·0	8·4	20·3	10·1
2 —2½	21·1	13·9	16·0	19·7	12·0
2½—3	18·6	9·9	9·0	22·7	12·4
3 —3½	21·3	12·2	12·0	20·6	13·8
3½—4	21·3	12·7	10·0	20·9	13·5
4 —4½	17·4	10·9	13·0	17·1	12·9
4½—5	16·7	11·3	14·0	14·6	10·3
5 —5½	18·1	16·0	14·0	16·1	13·9
5½—6	19·5	15·6	14·0	17·7	13·5
6 —6½	19·6	13·1	11·8	16·7	14·6
6½—7	18·5	12·8	13·2	15·7	12·5
7 —7½	20·0	20·1	17·8	18·2	18·2
7½—8	21·6	20·9	18·8	20·7	19·8
8 —8½	21·1	21·7	21·6	21·2	20·0
8½—9	19·6	21·1	19·6	19·9	19·9

Sown	November 3rd, 1908.		November 3rd, 1908.
Harvested	February 22nd, 1909.		March 2nd, 1909.
Area of crop which was weighed	147·5 sq. ft.		130 sq. ft.
Weight of dry matter — Seed	6·66 lbs.		3·67 lbs.
Pods	6·72 ,,		3·85 ,,
Straw	5·09 ,,		3·00 ,,
Fallen leaves	2·97 ,,		·34 ,,
Total	21·44 ,,		10·86 ,,
Dry matter per sq. ft.	·145 lbs.		·0836 lbs.
Lbs. water in unit column.			
Initial	174·4		163·6
Rain = ·32″	1·7		1·7
	176·1		165·3
Direct evaporation	7·		7·0
Remaining at harvest	126·0		118·7
Transpired	43·1		39·6
	176·1		165·3
Ratio	$\frac{43·1}{·145}$	=298	$\frac{39·6}{·084}$ =471

STATEMENT No. XIV.

PEAS, PUSA, 1908-09.

Depth ft.	Pounds of Water in Soil per Cub. Ft.				
	Manured.			Unmanured.	
	Initial, 9-12-08.	Harvest, 7-3-09.	5-5-09.	Initial, 17-12-08.	Harvest, 4-3-09.
0 — ½	15·9	4·1	8·6	11·0	3·6
½—1	17·3	9·0	11·6	14·4	8·3
1 —1½	19·7	11·6	13·0	18·7	12·0
1½—2	22·3	10·0	14·2	21·3	14·6
2 —2½	20·2	16·0	15·8	17·1	18·9
2½—3	19·7	11·3	13·2	21·6	20·4
3 —3½	20·1	13·4	11·6	21·2	17·2
3½—4	21·2	15·4	15·0	20·3	15·8
4 —4½	15·2	11·6	10·2	19·2	14·4
4½—5	20·5	16·7	16·8	15·6	13·2
5 —5½	19·4	16·3	13·2	15·6	13·4
5½—6	18·3	12·5	13·0	15·6	11·5
6 —6½	17·6	13·7	10·2	14·6	11·0
6½—7	17·0	10·5	9·8	13·6	11·2
7 —7½	19·3	19·4	17·4	17·0	15·4
7½—8	21·7	20·6	20·4	20·5	20·0
8 —8½	22·8	20·7	21·0	22·5	20·4
8½—9	19·6	20·8	19·8	19·9	21·4

Sown	November 3rd, 1908.	November 3rd, 1908.	
Harvested	March 7th, 1909.	March 4th, 1909.	
Area of crop which was weighed	143 sq. ft.	153·5 sq. ft.	
Weight of dry matter { Straw, pods, &c ..	8·23 lbs.	6·35 lbs.	
Weight of dry matter { Grain ..	3·03 ,,	4·03 ,,	
Total ...	11·26 ,,	10·38 ,,	
Dry matter per sq. ft.	·0787 ,,	·0678 ,,	
Lbs. water in unit column.			
Initial	173·9	159·8	
Rain ·38"	2·0	2·0	
	175·9	161·8	
Direct evaporation ...	9·2	9·2	
Remaining at harvest	126·8	131·3	
Transpired	39·9	21·3	
	175·9	161·8	
Ratio . ..	39·9 / ·079 = ·505	21·3 / ·068 = ·314	

STATEMENT No. XV.

Wheat, Pusa, 1909-10.

Pounds of Water in Soil per Cub. Ft.

Depth ft.	Manured.			Unmanured.		
	Initial, 14-11-09.	Harvest, 23-3-10.	23-4-10.	Initial, 10-11-09.	Harvest, 28-3-10.	28-4-10.
0 — ½	14·2	1·6	1·2	12·6	4·3	3·5
½—1	16·5	6·0	7·1	13·4	8·5	8·1
1 —1½	16·2	6·8	6·8	14·6	13·8	6·3
1½—2	16·9	8·7	10·0	14·1	12·9	9·1
2 —2½	16·9	7·9	8·0	16·6	8·8	8·8
2½—3	17·6	7·6	8·1	19·7	9·6	8·8
3 —3½	18·7	9·0	8·7	19·9	9·1	8·9
3½—4	21·8	9·1	9·1	20·8	11·9	11·0
4 —4½	23·2	10·0	8·6	20·6	12·4	10·6
4½—5	23·1	11·8	10·7	21·0	14·4	13·7
5 —5½	24·4	16·0	15·3	24·6	13·3	11·9
5½—6	26·3	15·1	13·6	21·5	14·8	13·4
6 —6½	23·8	18·7	18·9	23·4	20·7	20·2
6½—7	23·5	21·2	22·6	22·5	23·2	22·8
7 —7½	22·4	21·2	22·7	25·1	22·8	24·2
7½—8	24·8	22·6	24·7	25·4	24·8	25·6
8 —8½	25·0	23·3	24·5	24·6	23·9	22·4
8½—9	25·9	25·3	25·8	24·9	25·9	24·9

Sown	November 1st, 1909.	November 1st, 1909.	
Harvested	March 23rd, 1910.	March 28th, 1910.	
Area of crop which was weighed	60·0 sq. ft.	54·0 sq. ft.	
Weight of dry matter — seed	3·03 lbs.	1·83 lbs.	
Weight of dry matter — straw	5·53 ,,	3·73 ,,	
Weight of dry matter — chaff	1·66 ,,	·88 ,,	
Total	10·22 ,,	6·44 ,,	
Dry matter per sq. ft.	·17 ,,	·12 ,,	

Lbs. water in unit column.

Initial	190·6	182·6	
Rain = ·22″	1·1	1·1	
	191·7	183·7	
Direct evaporation	17·7	17·7	
Remaining at harvest	120·9	137·5	
Transpired	53·1	28·5	
	191·7	183·7	
Ratio	$\frac{53·1}{·170}$ =313	$\frac{28·5}{·120}$ =237	

STATEMENT No. XVI.

Oats, Pusa, 1909-10.

Depth ft.	Pounds of Water in Soil per Cub. Ft.		
	Manured.		
	Initial, 17-11-09.	Harvest, 14-3-10.	14-4-09.
0 - ½	12·8	1·4	1·6
½—1	13·8	3·3	5·6
1 —1½	13·1	5·2	6·4
1½—2	17·3	8·0	8·9
2 - 2½	17·7	9·7	11·0
2 —3½	16·8	8·4	9·1
3 —3½	19·5	9·8	9·8
3½—4	21·0	8·9	8·8
4 —4½	19·3	9·1	8·8
4½—5	23·7	15·3	15·4
5 —5½	25·2	12·3	11·0
5½—6	24·2	13·7	12·4
6 —6½	23·7	17·5	16·9
6½—7	23·2	21·7	21·4
7 —7½	24·9	20·8	22·7
7½—8	26·1	24·4	25·6
8 —8½	26·4	25·3	25·6
8½—9	27·2	25·2	27·2

Sown			November 1st, 1909
Harvested			March 14th, 1910.
Area of crop which was weighed			50 sq. ft.
Weight of dry matter	seed		3·60 lbs.
	straw, &c.		5·69 ,,
		Total	9·29 ,,
Dry matter per sq. ft.			·186 ,,

Lbs. water in unit column.

Initial	188·9
Rain ·22"	1·1
	190·0
Direct evaporation	17·7
Remaining at harvest	120·0
Transpired	52·3
	190·0
Ratio	$\frac{52·3}{·186} = 282$

STATEMENT No. XVII.

Linseed, Pusa, 1909-10.

Pounds of Water in Soil per Cub. ft.

Depth ft.	Manured.			Unmanured.		
	Initial, 21-11-09.	Harvest, 22-3-10.	21-4-10.	Initial, 21-11-09.	Harvest, 31-3-10.	30-4-10.
0 — ½	14·2	2·9	1·8	11·5	2·2	2·7
½—1	15·6	4·4	6·0	13·8	5.7	7·0
1 —1½	16·9	5·0	7·9	14·4	7·1	8·1
1½—2	15·0	5·7	5·9	12·5	6·7	6·5
2 —2½	13·9	6·5	6 0	14 9	6·0	6·5
2½—3	15·7	7·5	6·5	15·8	6·6	6 6
3 —3½	17·5	8·8	8·0	19·6	8·3	7·6
3½—4	19·1	9·1	7·5	21·7	9·4	9·0
4 —4½	19.6	9·7	8·2	19 3	14·7	14·4
4½—5	21·6	13·8	12·7	23·5	12·8	11·3
5 —5½	23·1	11·6	9·6	23 5	16·4	14·2
5½—6	23·8	13·1	11·1	23·7	18·4	17 2
6 —6½	25·7	17·8	16·3	24·4	21·6	20·7
6½—7	24·7	21·3	21·9	23·5	22·0	22·0
7 —7½	23·5	22·2	22·4	24·5	22·6	22·4
7½—8	24·4	23·4	23·6	25·5	23 0	22·3
8 —8½	25 5	23·2	22·5	25·5	25·0	23·4
8½—9	25·5	24·4	25·7	25·7	26·6	24·2

Sown		November 1st, 1909.	November 1st, 1909.
Harvested		March 22nd, 1910.	March 30th, 1910.
Area of crop which was weighed		60 sq. ft.	60 sq. ft.
Weight of dry matter	seed...	·91 lbs.	1·0 lbs.
	straw	2·01 ,,	1·75 ,,
	chaff	·31 ,,	·75 ,,
	Total	3·23 ,,	3·20 ,,
Dry matter per sq. ft.		·054 ,,	·053 ,,

Lbs. water in unit column.

Initial	182·6	181·6
Rain = 22″	1·1	1·1
	183·7	182·7
Direct evaporation	17·7	17·7
Remaining at harvest	115·2	127·6
Transpired	50·8	37·4
	183·7	182·7
Ratio	$\frac{50·8}{·054} = 940$	$\frac{37·4}{·053} = 706$

STATEMENT No. XVIII.

MUSTARD. PUSA. 1909-10.

Depth ft.	POUNDS OF WATER IN SOIL PER C.U. FT.					
	MANURED.			UNMANURED.		
	Initial, 22-11-09.	Harvest, 7-3-10.	7-4-10.	Initial, 23-11-09.	Harvest, 9-3-10.	10-4-10.
0 — ½	14·6	7·5	6·6	11·7	4·9	4·3
½—1	15·8	10·7	9·2	13·0	7·7	9·9
1 —1½	15·1	13·4	7·8	13·9	9·3	11·4
1½—2	17·2	12·3	10·2	12·9	8·6	7·5
2 —2½	15·6	9·4	7·8	15·9	11·1	9·6
2½—3	16·0	8·9	7·3	17·8	11·1	10·5
3 —3½	18·0	10·2	8·5	18·5	10·7	9·7
3½—4	19·8	10·4	8·7	21·1	13·9	12·5
4 —4½	20·3	10·0	8·4	22·6	15·6	12·3
4½—5	23·1	11·7	11·4	22·0	15·8	14·9
5 —5½	22·6	16·5	14·4	24·7	14·2	12·7
5½—6	26·2	16·1	13·5	25·0	14·4	15·3
6 —6½	25·2	19·7	18·4	23·8	22·3	17·3
6½—7	23·5	20·3	21·9	23·4	22·4	21·4
7 —7½	24·1	21·6	22·5	24·4	23·7	23·2
7½—8	24·5	21·6	24·0	24·4	24·6	23·6
8 —8½	25·4	23·8	22·9	24·7	25·3	24·0
8½—9	26·4	25·3	25·8	25·9	25·0	24·6

Sown		November 1st, 1909.	November 1st, 1909.
Harvested		March 7th, 1910.	March 9th, 1910.
Area of crop which was weighed		60 sq. ft.	60 sq. ft.
Weight of dry matter	seed	·88 lbs.	·90 lbs.
	straw	2·84 ,,	2·77 ,,
	Total	3·72 ,,	3·67 ,,
Dry matter per sq. ft.		·062 ,,	·061 ,,
	LBS. WATER IN UNIT COLUMN.		
Initial		186·7	182·8
Rain ·16		·8	·8
		187·5	183·6
Direct evaporation		14·7	14·7
Remaining at harvest		134·7	139·8
Transpired		38·1	29·1
		187·5	183·6
Ratio		$\frac{38·1}{·062} = 614$	$\frac{29·1}{·061} = 477$

STATEMENT No. XIX.

WHEAT, CAWNPORE, 1908-9.

POUNDS OF WATER IN SOIL PER CUB. FT.

Depth ft.	Initial.	Wheat plot A, harvest, 16-4-09.	Fallow plot D, 23-4-09.	Initial.	Wheat plot C, harvest, 19-4-09.	Fallow plot B, 22-4-09.
0— ½	12·2	2·6	16·6*	18·1	4·5	10·4*
½—1	16·7	5·1	9·2	18·7	4·5	5·8
1 —1½	15·9	6·0	9·8	21·6	7·7	7·1
1½—2	14·9	7·2	14·1	22·6	9·5	9·1
2 —2½	16·5	7·6	11·9	24·4	10·2	9·6
2½—3	14·2	8·0	13·3	23·7	10·3	9·9
3 —3½	17·8	9·1	13·0	25·2	12·2	10·5
3½—4	16·8	9·3	13·0	24·6	12·8	11·4
4 —4½	18·5	8·8	11·8	25·0	13·2	9·5
4½—5	19·5	9·6	9·7	22·4	13·1	10·1
5 —5½	18·7	9·5	12·0	25·1	13·8	11·6
5½—6	20·4	15·5	14·2	22·9	16·1	14·7
6 —6½	23·0	15·0	15·6	23·5	16·6	16·4
6½—7	24·4	15·7	15·7	24·1	16·8	16·5
7 —7½	26·5	22·2	16·3	27·1	19·0	21·7
7½—8	27·8	25·2	18·7	27·3	23·1	25·4
8 —8½	30·4	22·0	19·4	31·4	25·9	24·8
8½—9	31·4	21·5	22·8	30.3	28·0	24·3

	A.	*C.*
Dry matter per sq. ft.	·117 lbs.	·110 lbs.
	LBS. WATER IN UNIT COLUMN.	
Initial	182·8	219·0
Rain=·25″	1·3	1·3
Irrigation	27·1	27·9
	211·2	248·2
Direct evaporation	49·6	64·6
Remaining at harvest	109·9	128·6
Transpired	51·7	55·0
	211·2	248·2
Ratio	$\frac{51·7}{·117}$ = 442	$\frac{55·0}{·110}$ = 500

* Rain fell on both these plots before they could be sampled.

STATEMENT No. XX.

WHEAT, CAWNPORE, 1909-10.

POUNDS OF WATER IN SOIL PER CUB. FT.

Depth ft.	Plot B, Wheat.		Plot A, Fallow.		Plot D, Wheat.		Plot C, Fallow.	
	Initial, 1-12-09.	Harvest, 9-4-10.	Initial, 29-11-09.	4-4-10.	Initial, 2-12-09.	Harvest, 7-4-10.	Initial, 30-11-09.	5-4-10.
0 — ½	5·2	2·0	8·3	5·6	6·3	2·5	7·4	4·3
½—1	10·7	5·5	12·4	8·9	10·9	5·8	11·0	8·8
1 —1½	12·5	5·5	14·1	10·5	13·7	7·4	12·8	10·8
1½—2	14·0	5·4	14·6	11·4	15·0	7·2	14·8	13·8
2 —2½	14·3	4·6	15·3	13·5	14·4	6·2	15·4	16·2
2½—3	14·9	4·9	13·0	13·0	14·0	6·0	14·8	15·8
3 —3½	14·2	5·6	12·6	10·0	13·3	6·8	15·1	19·3
3½—4	14·5	5·8	12·8	11·0	13·5	7·8	14·9	19·0
4 —4½	12·9	6·0	13·0	10·4	13·7	7·8	17·4	17·3
4½—5	12·8	6·8	14·4	14·0	12·0	9·7	16·2	16·5
5 —5½	15·2	10·1	15·4	15·4	13·3	11·0	17·0	14·1
5½—6	16·9	11·5	16·6	14·1	15·2	12·5	16·2	15·0
6 —6½	18·5	14·7	17·9	17·5	15·5	14·5	17·8	17·3
6½—7	20·8	16·1	21·2	19·8	16·3	14·6	19·4	16·2
7 —7½	24·5	18·0	26·0	23·3	18·0	17·1	20·3	19·6
7½—8	26·1	24·8	29·2	24·7	20·7	20·7	26·3	22·7
8 —8½	26·9	21·1	28·4	25·6	24·7	22·8	26·9	23·4
8½—9	26·5	16·9	29·0	26·5	23·0	21·8	27·7	24·4

	B.	*D.*
Dry matter per sq. ft.	·1615 lbs.	·1588 lbs.

LBS. WATER IN UNIT COLUMN.

Initial	150·2	136·7
Rain = 1·81″	9·4	9·4
Irrigation	26·0	23·7
	185·6	169·8
Direct evaporation	27·4	20·8
Remaining at harvest	92·6	101·1
Transpired	65·6	47·9
	185·6	169·8
Ratio	$\frac{65·6}{·161} = 407$	$\frac{47·9}{·159} = 302$

CHART VIII.

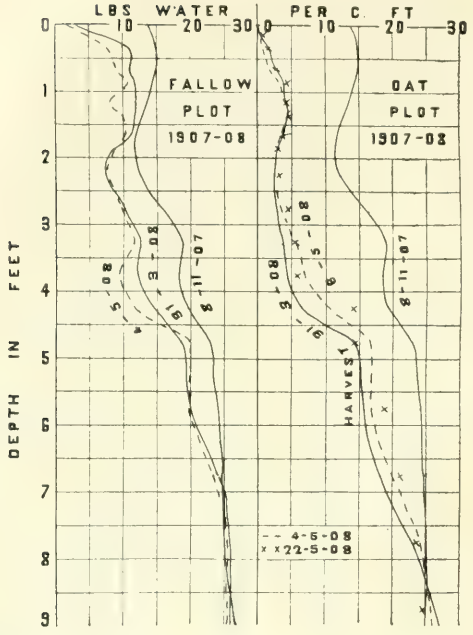


CHART XIV.

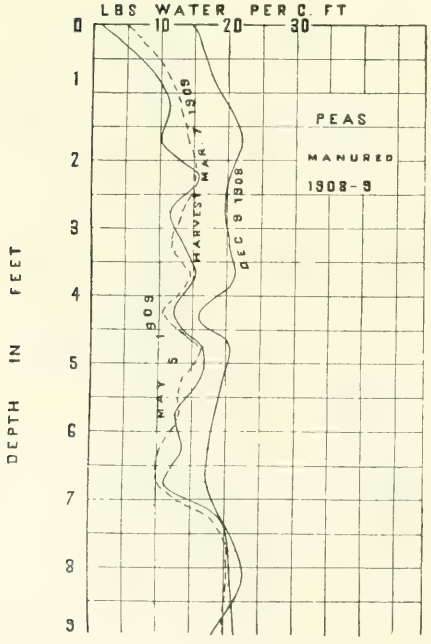


CHART XIII.

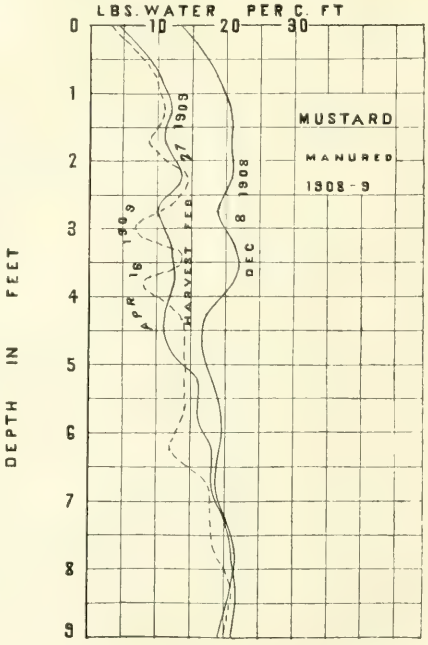


CHART XV.

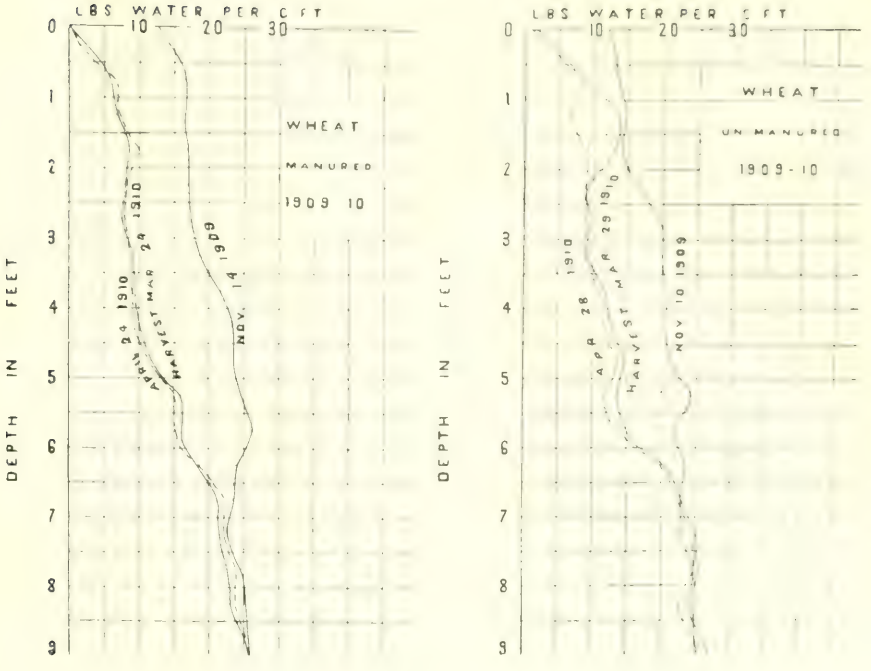


CHART XVI.

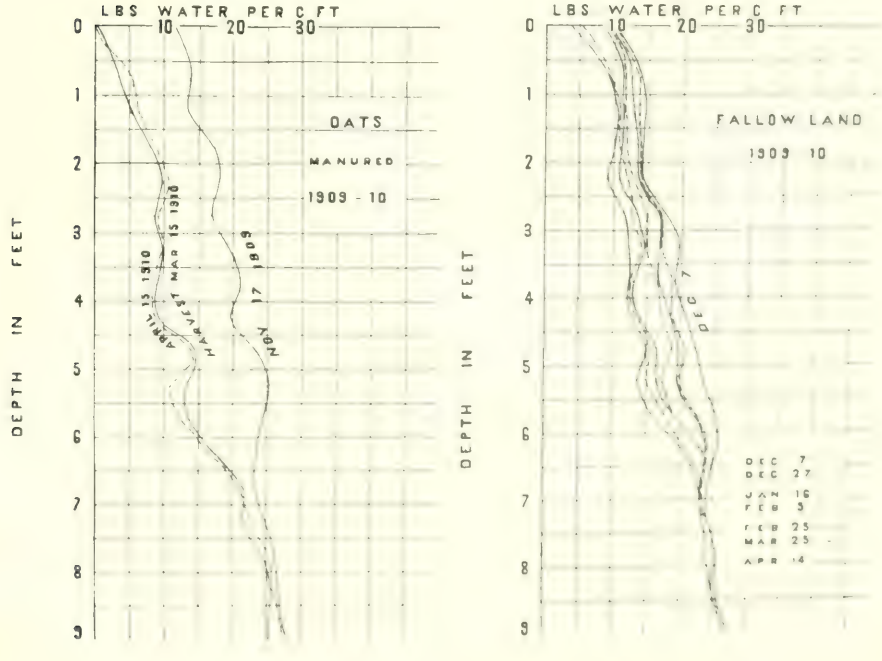


CHART XVII.

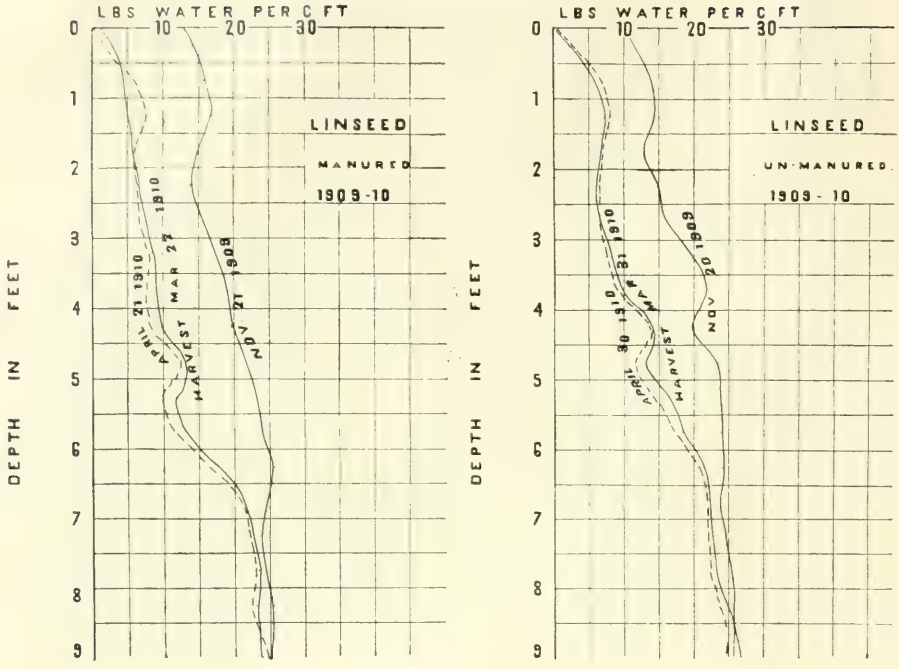
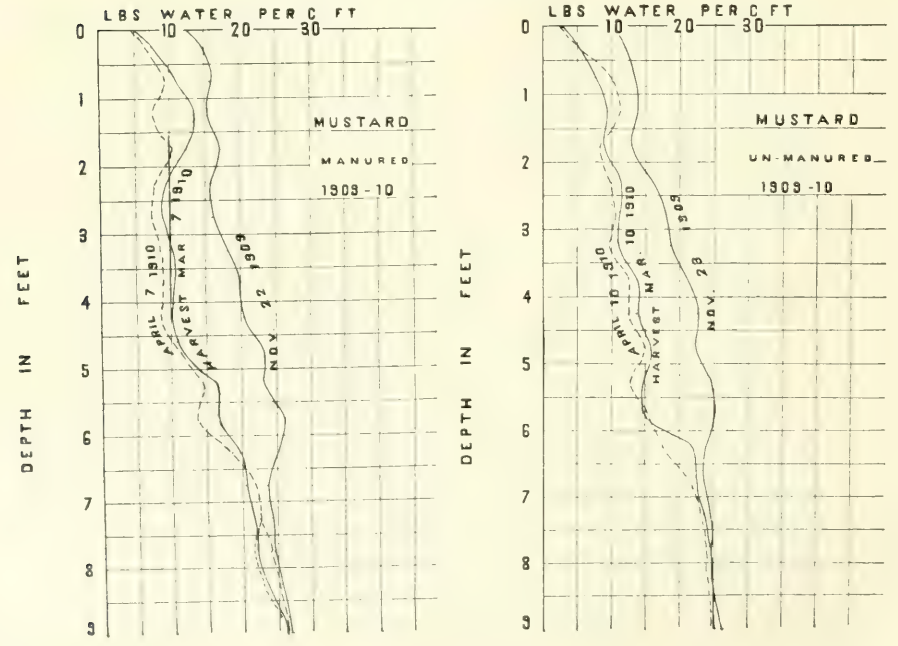


CHART XVIII.



Another fact brought out by the decrease of water concentration through crop agency is that the decrease is more or less constant throughout 5 or 6 feet. The general idea is that, although some roots extend through a number of feet, the greater part of the root system develops in the first foot or so of the soil. As a matter of fact we are not concerned here with either the total length of the root system or with the number of roots, but purely with the organs which assimilate the water, and the question one would like to answer is what is *their* distribution and how far apart are they? I trust this does not read as though it is suggested that such organs take up fixed positions in the soil; it is, of course, perfectly well understood that they have a temporary existence, and that as each fulfils its allotted task and dies off, it is followed by a new one further on. But they must be distributed in some systematic manner, and judging by the magnitude of the decreases of water in succeeding feet of soil they seem to have been nearly as numerous in the fifth and sixth feet at Pusa as in the first. In the irrigated soil at Cawnpore the case is nearly the same, though after allowing for the irrigation water, there must have been more water assimilated in the first and second feet than in the fourth and fifth feet.

The amount of Water transpired.—As explained in the Introduction, the object of these field tests was not limited to obtaining information in regard to decreases of soil moisture due to crops, and the extent in the sub-soil to which such decreases occur, but also to try to estimate the amount of water transpired, and to compare this with the weight of crop grown, in order to ascertain whether this ratio agreed substantially with that which has been obtained by pot-culture methods

Now it is not feasible to estimate directly the quantity of water which is brought to the surface of the land and evaporated or the quantity transpired by crops. I considered at one time whether it would be possible to so enclose a portion of a crop that, if air were passed freely over it, the increase of moisture in this air could be determined with a sufficient degree of precision,

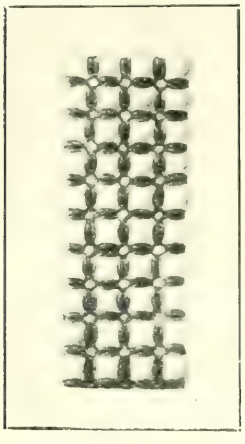
and it became evident that such a method would be quite impracticable. Only one of a number of difficulties need be here stated. Suppose that a part of a crop were enclosed in an apparatus which would cause no abnormal solar or radiation effects and air were uniformly passed over the crop, the error in determining such differences of atmospheric humidity, whether measured daily or half-daily or for any other period of time, would be too great to admit of the necessary precision. It must be recollected in this respect that ordinary air must be employed, containing, say, 75 per cent. humidity, and that if, while such air were passing over the crop, the transpired water raised the humidity to say 85 per cent., changed conditions would be thereby introduced, which could not fail to affect the rate of transpiration, and yet even with so small a difference of humidity between the air before and after passing over the crop, it would be impossible to determine with sufficient precision the respective amounts of water. Such a method of directly estimating the amount of water transpired by a crop is then for these reasons alone impracticable. Numerous other difficulties also arise, some of which are equally weighty.

It is, however, possible to employ an *indirect* method, provided it is allowed to be a sound one.

In Memoir No. 6 and *Nature*, Jan. 14th, 1909, I gave reasons which were based on arguments used by Lyman Briggs,* for assuming that, if a series of soil moisture determinations are made throughout succeeding strata of soil, and it is found that no change of concentration occurs during the period of observation below a certain depth (provided also that the sub-soil water is at least some feet below this stratum), it may be held that no material amount of movement of soil moisture has occurred from this depth during the period. The data quoted in that memoir dealt with changes of soil moisture in fallow land during dry weather, but the arguments there used are of quite general application. It is perhaps necessary to recapitulate them here in order to show their connection with the experiments on

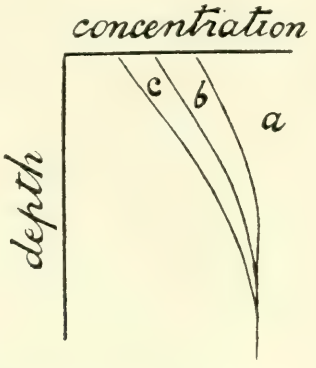
* Bull. 10, Division of Soils, U. S. Dept. Agric.

crops which are now under review. Briggs assumed that the water in soils (*i.e.*, the liquid water) is retained, after drainage has ceased, between soil particles in the manner indicated in the marginal figure. It is, of course, well understood that a mass of soil does not consist simply of particles arranged in the simple geometric manner that the spheres occupy in the illustration, much less that they are spherical or all of one size; it is indeed probable, though the fact has not been demonstrated, that collections or aggregates of soil particles occur, which aggregates owe their existence to the surface tension of the water between them. But whatever the real arrangement of particles in the soil, the movements of water after drainage has ceased must depend on changes in the quantity of water between neighbouring particles, which produce differences in surface energy. And Briggs pointed out that, if at any point water is removed from between two particles, this will occasion a change in the curvature of the surface of the water remaining, which will cause a flow of water from between the neighbouring particles, and this motion will be communicated throughout the whole mass. This argument has been generally accepted as sound.



Founded on this the further argument follows that, supposing water to be abstracted from any part of such a system, and a series of moisture determinations be made across the direction of the flow of water before the effect of this water movement has had time to cause a *measurable* effect at the further end of the system, a decrease of water concentration will be found throughout, though the magnitude of this decrease will diminish towards the further end of the system. If now a second series of such determinations of water-concentration be made after a time interval insufficient to admit of a *measurable* effect at the further end of the system, the concentration will be found to have further

decreased in each succeeding plane. In fact the periodical concentrations may be illustrated by the diagram below. In it the curves b and c represent the subsequent concentrations of water and are drawn cutting the curve a of initial concentration. Very probably they meet it asymptotically, but this fact



would not materially affect the question. This movement of water *must* be accompanied by a decrease of concentration, and hence it follows that the area between the curves a and b would express, within the limits of experimental error, the total quantity of water which had flowed through this part of the system during the period of observation. There are experimental difficulties in making the series of water determinations with precision, the changes in concentration in that part of the system which is represented by the lower end of the curves being particularly difficult to ascertain, but this does not affect the principles involved.

There is I think a popular belief that, so soon as water commences to evaporate, say, at the surface of land there is an upward movement of water towards the surface from all depths. On the contrary, the movement is not immediately communicated throughout. Far from such being the case, considerable periods of time may be required for such a movement of water which originates (in the example just mentioned) at the surface, to be communicated through a number of feet of soil. This will perhaps be best demonstrated by the following line of argument. Suppose after a period of dry weather a fall of rain, say 1″,

occurs, succeeded by fine weather. This 1″ of water will soak into the upper soil and a series of water determinations would show its distribution. Suppose it were found to be distributed through the first 6″. Now the difference in water concentration existing between the first 6″ and the next would cause this water to move downwards, which motion would continue in the downward direction until the surface energy of the water between all particles became equal. Such a process would take time, but changes would be *perceptible* for several days. On the other hand, however, fine weather is supposed to have set in and this necessarily occasions *evaporation*, accompanied by a movement of water towards the surface. We have then water moving *at the same time* in both directions. The case may be illustrated graphically as in the four small charts.

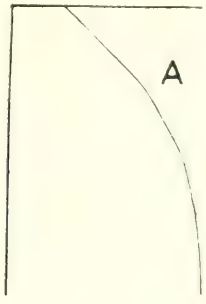


Fig. 1.

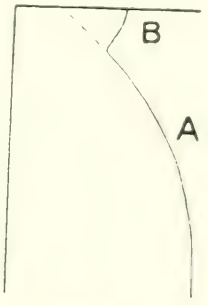


Fig. 2

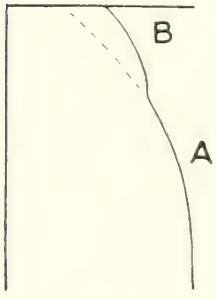


Fig. 3.

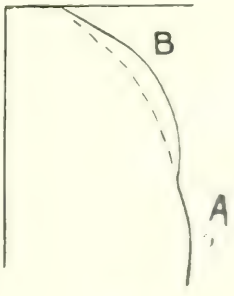


Fig. 4.

The curve A in Fig. 1 represents the initial concentration of water: in Fig. 2 the added curve B represents the first effect of the rainfall whilst the Figs. 3 & 4 illustrate how this "wave"

of moisture spreads itself downwards, whilst concurrently evaporation at the surface reduces it there, and the "height" of the wave constantly diminishes. An example of this was recorded in 1908 and the data are set out in the Statement No. XXI. On August 12th after a long "break" in the rains, 1·34″ of rain fell. A moisture record had been kept in a plot of fallow land, and the concentration of water on August 6th is shown in the first column. After the rainfall, moisture determinations were made on 13th, 15th, 17th and 19th. After the 12th the following rain fell: ·02″ on 17th and ·06″ on 19th.

STATEMENT No. XXI.

SHOWING THE EFFECT OF A "WAVE" OF DRAINAGE.

DEPTH.	6-8-08.	13-8-08.	15-8-08.	17-8-08.	19-8-08.
0″—3″	6·75	14·42	10·75	8·60	6·62
3″—6″	9·98	13·94	11·55	10·83	10·42
6″—9″	11·72	14·18	12·28	11·27	10·42
9″—1′	11·23	11·51	12·08	10·42	12·56
1′0″—1′3″	10·30	9·45	10·95	9·13	10·18
1′3″—1′6″	8·20	7·03	8·38	8 89	10·14
1′6″—1′9″	8·69	7·31	10·50	6·46	8·12
1′9″ -2′0″	7·23	5·29	7·11	7·35	7·11

Thus the first day after the rain, the water had spread itself through about 9″ of soil; two days later the moisture had increased in the next lower 3″ but had decreased again throughout the upper 9″; on 17th a further decrease was noticeable in the top 3″, but other changes had become too small to estimate; after this date further changes could not be determined though they must have been still in progress. Similar changes must occur after every irrigation. The same must constantly occur especially in countries which have a well distributed rainfall. It is known that drainage does not cease in, at least many, soils at 6 ft. for days, and judging by the difference of time required for drainage to cease in drain-gauges at 3 ft. and at 6 ft. respectively, at 10 or 15 ft. from the surface drainage must

continue for a week or more after rain ceases; but in the event of fine weather, water is nevertheless evaporating concurrently at the surface, and there is necessarily a movement through some part of the soil towards the surface, *i.e.*, it must, in such countries, be constantly the case that in one and the same soil water is, in the upper part moving towards the surface, in the lower part moving downwards.

These examples show how readily it may be that soil moisture, even in the protracted periods of dry weather which occur in India, is not necessarily moving through all distances in the soil simply because it is known to be moving through a certain part or stratum of it.

In order to fix ideas regarding the measurement of the total quantity of water which has moved through a soil in a given time, take the case of the Pusa soil, fallow, 1909-10, in which the series of measurements of water-concentration were made and which are illustrated in Chart No. XVI. The rainfall of the period was ·22″ which was obviously insufficient to affect the argument we are considering. This record shows that there was a gradual decrease of soil moisture in the upper $6\frac{1}{2}$ft. of soil, but that no measurable decrease occurred below $6\frac{1}{2}$ft. It has been argued (*Nature*, Augt. 8th, 1909) that because no decrease was observed below this depth, is no proof that there was no upward movement: but since any upward movement is necessarily accompanied by a decrease of concentration, this fact is a proof that the amount of upward movement below 7 ft. is extremely small The real defect lies not in the argument, but rather in the accuracy of the measurement. If the latter were more exact, there would be found at the end of each succeeding period of time a decrease in a lower stratum than had been found to be the case at the preceding date. The changes in the upper 4 or 5 ft. of this soil are so great that they are readily measurable by our method; this is a light soil for the most part through which water can move freely. But below this in the clay the movement of water is necessarily slow, changes of concentration are therefore small, and hence the difficulty of determining them.

And what applies to fallow land applies likewise to the soil from which water is being abstracted by plant roots. The examples of this effect which have been quoted show how, at harvest time, a greater decrease of soil moisture has occurred under the influence of a crop, and that this effect is easily measurable to one or to two feet deeper than where the land is merely evaporating water at the surface; but the *nature* of the changes are the same. In some cases there is a doubt whether the moisture determinations were carried as deep as might have been wished, but since the inaccuracies of the method have been so fully admitted, it will be sufficient to say that the observed change of concentration of moisture where a crop is grown should correspond approximately to the total amount of water which has been transpired by the plant and evaporated directly from the soil.

Calculations to this end for each of the crops have, therefore, been made in order to compare these quantities with those estimated by pot-culture methods.

It will be readily appreciated that whilst the total change of water-content in the unit column of soil can be simply estimated from the observed changes of concentration, such estimate includes the water which has been withdrawn from the soil by both agencies, transpiration and evaporation, whilst we desire information regarding the former as distinct from the latter. Although there is no method for the direct experimental estimation of the quantity evaporated, an attempt has been made to form at least a conception of it.

This estimate is made as follows: While the crop is young and transpiring only nominal amounts of water, the *evaporation* must be very similar to what would occur in the same soil if fallow. After this period, however, the crop shoots rapidly and covers the ground, either entirely or in a great measure. Now there are three reasons for assuming that this must necessarily very largely restrict direct evaporation: (*i*) since the plant is constantly transpiring large amounts of water, the atmosphere in between the leaves and stems must be highly saturated with water

vapour; (*ii*) the stems and leaves of the plants being close together, air movements are largely restricted, so that the highly humid atmosphere among the plants is held in position as a covering over the soil, and would necessarily reduce evaporation below what would occur into a dry atmosphere; (*iii*) the plant reduces the concentration of moisture in the top-most soil, and since a relatively dry soil will evaporate less water per unit time than a moister one, this effect of the plant will also tend to reduce direct evaporation. Some very interesting information in respect of the humidity of the atmosphere within a crop was published by Yapp* whose experiments demonstrate the fact that this part of the atmosphere is very highly charged with water vapour.

Data which have been obtained during three years by means of the drain-gauges, two of which are fallow and two cropped, indicate that where a good *rabi* crop is growing, the amount of water which simply evaporates from the soil, as distinct from that transpired, is only about one-half of what it would be if the land were fallow. For the purpose of estimating the amount of water transpired by the crops, this proportion has therefore been adopted. The data which have been utilised are all set out in the lower part of the Statements Nos. VIII to XX. After details regarding the weight of the crop, a "balance sheet" has been made to account for the water involved in each case. Thus we have the water in the soil at sowing time; this is styled the "initial" water. If the rainfall (and irrigation in the Cawnpore experiments) be added, the sum is the total water involved. On the other side of the account we have its disposal, which includes (i) *direct evaporation*; (ii) the *water remaining in the soil at harvest*; (iii) that *transpired*, which is obviously obtained by difference. This quantity may then be divided by the weight of the crop, and this ratio compared with that obtained in the pot-culture house. The results of such calculations are here collected in Statement No. XXII.

* Yapp, Ann. of Bot., Lond., p. 277, [illegible].

STATEMENT No. XXII.

TRANSPIRATION RATIOS OBTAINED BY (*a*) POT-CULTURES AND (*b*) FIELD METHOD.

CROP.	By Pot-culture.	By field method.				
		Pusa.			Cawnpore.	
		1907-08.	1908-09.	1909-10.	1908-09.	1909-10
Oats	400— 500	411	230 : 331	282	...	...
Wheat	450— 650	...	415	313 : 237	442 : 500	407 : 302
Barley	450— 650	..	341 : 430	...	...	..
Peas	600— 800		505 : 314	...	..	..
Linseed ...	600—1000	..	718 : 693	940 : 706	...	..
Mustard ..	400— 550	...	298 : 471	614 : 477	..	...

The pot-culture ratios quoted are those for small and large crops respectively, but since the crops grown in the field were in nearly all cases heavy ones (the cereals were all equal to or greater than 5,000 lbs. per acre), the field ratios should be comparable rather with the lower than with the higher pot-culture ratio. An examination of these ratios admits of the following conclusions :—

(i) They vary among themselves, but not to a greater degree than has been found in pot-culture experiments ;

(ii) the comparison between the ratios obtained by the two methods shows that, for oats it was generally less in the field, for wheat it was low in three out of seven tests, for barley about normal, for the other three crops the field ratios were frequently higher than the pot-culture ratio. If the comparison of the whole of the tests be made irrespective of crop, there are nearly as many field ratios higher than, as less than, the pot-culture ratio.

Looked at as a whole the nett result of this part of the investigation has been to yield ratios which certainly support the pot-culture work as well as could be expected of the

method. There are two points which may be here suitably referred to. (i) The pot-cultures have shown uniformly that the larger the mass of earth in which plants grew, the lower became the ratio, and consequently, unless in our pot-culture tests the quantities of soil employed have been sufficient to produce a maximum effect in this respect, the transpiration-ratio of crops growing in the field, where the mass of soil at the disposal of the crops is so very much larger than that employed in our largest pot-culture jars, might be expected to be lower than that obtained by the pot-culture method. Thus this factor must be assumed to be one of the causes tending to low field ratios. (ii) Some water would move upwards undetermined by the method employed. An instance which is of considerable value in showing how small this is may be here quoted.

In 1908, at the end of a very weak monsoon, some land which had borne grass was cleared, and prepared for "cold weather" sowings. Only very trifling amounts of drainage had occurred at 3 ft. and 6 ft. from the gauges during the monsoon and the grass had not only assimilated the rainfall, but, as the record showed (see adjoining Statement No. XXIII), it had depleted this land of a large amount of its moisture; the defect being from one-half to three-quarters in the upper 6 ft.: *below which the concentration of water was about normal.* Seed sown on this soil in October germinated very badly, and the subsequent growth was so poor that no weight of the crop was kept, but the moisture present in February was estimated and is included in the Statement. If as much as 10 pounds of water per unit column of soil had come up from below 9 ft., it should have been able to support a crop of (say) 600 or 700 lbs. of dry matter per acre, whereas the one which actually struggled for existence was far below even this small figure. Better evidence of the inability of the large stores of water contained in the soil below the root range to serve a crop could hardly be provided, and it can only be explained on the assumption that this water is moving extremely slowly.

Statement No. XXIII *showing concentration of water in Pusa soil* (a) *under normal condition*, (b) *after grass coupled with weak monsoon.*

Depth ft.	Pounds of Water per Cub. Ft.		
	(*a*)	(*b*) 14-10-08.	Barley plot. 1-2-09.
0 — ½	14·2	6·5	1·8
½—1	15·6	9·3	4·8
1 —1½	16·9	8·4	5·8
1½—2	15·0	7·7	6·7
2 —2½	13·9	5·8	4·8
2½—3	15·7	6·9	4·3
3 —3½	17·5	5·1	4·9
3½—4	19·1	5·1	5·5
4 —4½	19·6	4·8	5·1
4½—5	21·6	7·3	7·9
5 —5½	23·1	.....	11·1
5½—6	23·8	6·3	10·5
6 —6½	25·7	.....	14·9
6½—7	24·7	22·6	20·2
7 —7½	23·5	.....	23·3
7½—8	24·4	25·0	21·9
8 —8½	25·5	.....	25·2
8½—9	25·5	25·8	26·5

Changes of concentration of water in the soil subsequent to harvest.—The fact that a certain amount of water will move upwards undetermined by the change in moisture concentrations between two dates, has been referred to, but it was argued that it must be only small. In order to try to form a conception of its amount the following tests were made. It has been demonstrated that the concentration of water is generally decreased to a greater degree where a crop has grown than where the soil is merely left fallow. Thus at harvest throughout several feet of soil there is a deficiency of water. What is to be anticipated after removal of the agent, that is, the crop, which has created such deficiency? Will not this soil stratum, in which the deficiency has been created, tend to hold any water that is moving upwards so as to resume the higher degree of moistness which it would have contained had it been merely fallow?

In order to test this question, determinations of the moisture in the soil a month or six weeks after harvest have been made in each year, and the data relating to these are included in the Statements Nos. VIII and XIII to XVIII. In 1908, after harvesting

the oat crop, moisture determinations were made five and seven weeks respectively after harvest: during the former period there was no rain, but ·53″ fell on May 7th, that is, at the commencement of the second period. This fall which is equivalent to 2·8 lbs. per sq. ft. is unimportant in respect of the matter we are considering, since it could not appreciably affect the soil moisture below the first foot. A comparison of the concentration of water in the several feet, more especially between 2 and 7 ft. deep, shows that there was a distinct increase of soil moisture after harvest, which was accompanied by a decrease below 8 ft. In 1909 about two months after harvest, two tests were made in the mustard and peas plots respectively (Statements Nos. XIII, XIV). The rain which fell on the former plot amounted to ·51″, on the latter 3·47″. The former is of no consequence. The latter included two principal falls, namely, 1·15″ on April 18th and ·91″ on April 29th which was 7 days prior to the second determination of moisture. Although the effect of the 1·15″ would have practically disappeared before the determination of May 5th, that of the latter would hardly have passed off, though it could only materially affect the first foot. As a matter of fact on May 5th the first 6″ was distinctly moister than on 7th March. Neither of these records possess the same regularity that characterised the first test in 1908. In 1910 tests were taken a month after harvest in all the seven plots. The rainfalls of the several periods were of no consequence. Here the results possess considerable regularity. As the curves show, there was an increase in the 9th and 8th feet in four plots, a decrease in one plot and no marked change in two; above the 8th foot there was a general decrease. As a matter of fact, the test is by no means a very delicate one for the end in view. Any such remoistening must necessarily be the difference between the water received from below and that which is evaporating, and assuming that the soil does tend to hold water in the manner suggested, the nett augmentation of water will presumably depend in a great measure on the degree to which the crop desiccates the sub-soil beyond what would occur if no crop were

there; in other words, if, in the sub-soil at harvest, there is a *large* deficiency of water due to the crop, the tendency subsequent to harvest would presumably be for a relatively large accumulation of water in this part of the sub-soil, whilst if the effect of the crop is only to cause a small deficiency, the subsequent accumulation of water would likewise be only small. Thus, of all the crops, the oats of 1907-8 caused the greatest deficiency, namely, about 40 lbs. in the unit column; among the crops of 1909-10 wheat (manured) caused a deficiency of 26 lbs., oats (manured) caused one of 27 lbs. and the manured linseed one of 32 lbs. of water; of these the first three were followed by a subsequent accumulation of water in the sub-soil after removal of the crops, whilst the last was followed by a further decrease. The other crops created only small deficiencies of water and no accumulation was perceptible in them subsequent to harvest. The fact, however, of it being so difficult to detect this change, which on theoretical grounds should occur, is a further indication of how small must be the amount of water which is moving upwards during dry weather in this particular soil from below 8 or 9 ft.

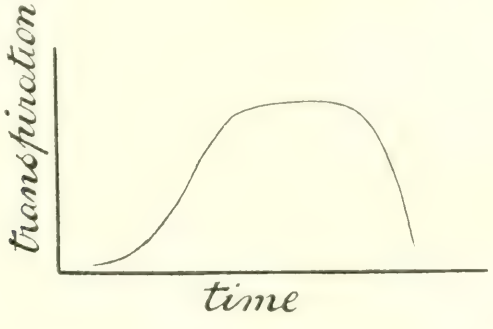
In the foregoing paragraphs evidence has been adduced to show that the quantity of water which rose in the Pusa soil undetected must have been less than 10 lbs. per sq. ft. of cross section. But it must be recollected that there is nothing to show that the quantity was as much as even one pound. The somewhat lower transpiration ratios found for some of the field crops would be as easily accounted for by the greater mass of soil as by an undetected quantity of water.

The quantity of water present within the root range.—The available information in respect of root development is admittedly very limited, but crop roots have been traced through a number of feet.

Assuming that the decrease of soil moisture as exhibited by the Charts Nos. VIII & XIII—XVIII indicate the active root range, this amounts to 7 or 8 ft. Now the amount of water

present in the unit column of soil at sowing time has been found to be from 150 to 200 lbs. in the soils at Pusa and Cawnpore: or deducting 25 lbs. for the 9th foot of soil, it is evident that the total quantity of water present is from two to four times as much as heavy crops require.

The daily requirement of water by a crop during the period of maximum assimilation.—On page 178 of Memoir No. 8 it was pointed out that the greater part of the water required for the development of a crop is assimilated during a limited period. The curves deduced from the pot-cultures are all similar in showing that there is a period of maximum transpiration, and neglecting the temporary effects of temperature and humidity, it may be represented by the curve shown below.



From the curves which have been obtained it is easy to calculate approximately the mean amount of water daily transpired during the period of greatest assimilation, and thence, on the assumption that this mean quantity is proportional to the weight of crop, to reduce the results of all experiments either to one common standard of crop-weight or to a limited number of such weights. Such a calculation would provide an indication of the amount of water required per day during the period of maximum assimilation by a crop of standard weight. The assumption that the weight of water transpired is proportional to the weight of crop we know to be not strictly the case, and hence to make the calculations indicated is not free from objection. Nevertheless the information obtained, although only approximately correct, is of interest in relation to what follows.

The following Statement No. XXIV exhibits the quantities of water so required.

STATEMENT No. XXIV.

Crop.	Standard weight. lbs.	Water required per sq. ft. of land per day. lbs.	Period during which maximum water requirement continues. Days.
Wheat ...	5,000	·7	40
Barley ...	5,000	·6	40
Oats ...	5,000	·6	40
Sarson ..	5,000	·6	40
Linseed ...	3,000	·8	30
Peas ...	5,000	1·0	30
Gram ..	5,000	1·1	40
Maize ...	5,000	·4	40

For the "standard weight," which naturally includes straw, leaves, etc., as well as grain, quantities have been taken which will be open to criticism because the weight of a "heavy" crop varies so much in different localities. The period also during which the major part of the water is transpired will also vary with the climate.

Factors regulating movement of water.—The field experiments which have been dealt with in the previous paragraphs have demonstrated four facts :—

(i) The quantity of water within the root range was far in excess, from two to four times as much, of that which heavy crops require.

(ii) That during growth a marked decrease of water concentration occurs through 7 or 8 ft. of soil, which coincides with the root range so far as we have information on the subject.

(iii) That after a normal monsoon the Pusa soil, if it has been fallow, can support a heavy cold weather crop without material additions of water ; on the other hand, the Cawnpore soil is unable to do so.

(iv) That if a soil like that at Pusa is largely depleted, *within* the root range, of its usual store of water, but contains *below* the root range a normal and large amount of water, the latter is practically of no use to the crop.

Now, these several facts, as well as each of the other features which have been dealt with, would be accounted for if the water supply through the soil to the plant were controlled under the influence of surface tension, by a law similar to that which governs the transmission of heat or the diffusion of salts. Doubtless the cases are not identical, and the movement of water through soils is probably not so simple. Nevertheless if the chief factors are the same, the quantity moving per unit time would vary, (i) directly as the difference of concentration of water at the two ends of the column, which difference might be styled "potential," (ii) inversely as the square of the distance, (iii) directly as the magnitude of some "constant" peculiar to each soil.

Thus in any one soil, the plant would receive more water per hour or day, the more water is present in the soil, and the shorter the distance through which the water has to travel.

The action of the root will be to lower the concentration of water in its immediate neighbourhood, and water will flow towards it horizontally as also from below. The following typical cases may now be considered.

(*a*) The soil contains abundance of water for the requirements of the root *within its length* and water moves freely through the soil. Then the root's requirement will be satisfied by a comparatively small lowering of the water concentration in the soil throughout the root length. Water will tend to move upward from below to increase again this reduced concentration, but as the distance below the root range increases, the quantity moving will rapidly diminish. Example, Pusa soil.

(*b*) The soil contains similarly large proportions of water, but water cannot move freely through the soil. The root would be served with a deficiency of water resulting in a small above ground growth. It would be just as difficult for water to move from below. Example, Cawnpore soil.

(*c*) The soil, say a sandy one, contains too little water within the root range for a heavy crop, but water moves freely through it. Owing to low concentration the root would be served badly

with water within the root range and water would tend to move upwards, but as the concentration below the root fell and the distance through which the water would have to move increased, its quantity would fall off rapidly.

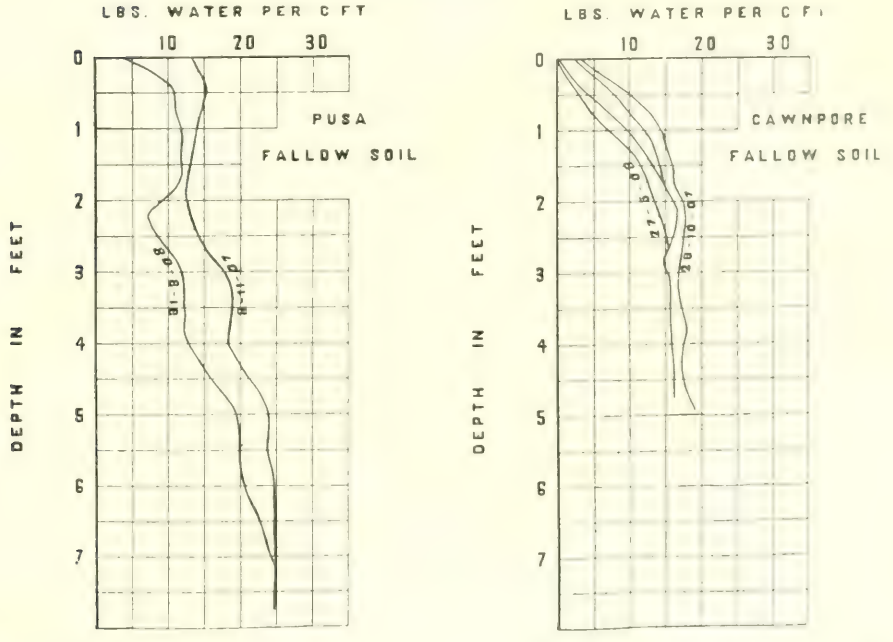
(*d*) The soil within the root range contains too little water for a heavy crop, but contains abundance one or two feet below the root system; water can move freely through the soil. Here the root would be served badly by the soil within its length owing to low concentration; from below the quantity of water moving per unit time would be small on account of the great distance through which it would have to pass to the root. Example, Barley crop on Pusa soil, 1908-09 (page 271).

In the foregoing it has been assumed that the roots are assimilating water throughout the whole length of the root-range at the same time. As a matter of fact but little is known about this matter. It may be that the assimilation proceeds largely inch by inch and foot by foot as the root system develops, resulting in each layer or stratum of soil being largely depleted of its water successively; or it may be that the root extension is so rapid that the reduction of concentration occurs more or less simultaneously in the whole column of soil. It may be mentioned, however, that in the drain gauges, roots come through the false bottoms at 3 ft. when the crop is quite young, and this has also occurred at Cawnpore in the six-foot gauges. Such evidence would indicate the second of the above suggestions as being nearer the truth. However this may be, the final state of the soil moisture corresponds with what would be expected if the quantity of water moving through a soil to a root system obeyed a law similar to the one which has been set out. There is a large and nearly uniform decrease of concentration in the upper 5 or 6 ft. of soil, below which the decrease becomes rapidly small.

The decreases of water in fallow land during dry weather also agree well both with the soil's ability to support vegetation as also with what a law such as that suggested would demand. The accompanying Chart XXV shows the concentration of water in fallow soil at Pusa and Cawnpore respectively in 1908. The

shape of the curves of the one is characteristically different from that of the other; that for the Cawnpore soil being much the steeper. Such a difference of shape would indicate the Cawnpore soil to be a worse "conductor" of soil moisture than the Pusa soil. If such were the case, the Cawnpore soil would lose less water into the atmosphere during dry weather: its water would also move to the plant root less readily. As already mentioned, the latter

CHART XXV.



feature would tend to the production of a smaller crop at Cawnpore than at Pusa, which is known to be the case.

It may be stated indeed as a general rule that among soils which are fairly homogeneous throughout the upper 7 or 8 ft., those which lose much water when fallow during dry weather will serve the crop's root system well with water: those on the other hand, which dry principally at the surface but lose on the whole but little water, will serve the crop badly and require either rain or irrigation.

Conclusions.

(i) The transpiration ratios obtained with other soils than that of Pusa show that the nature of the soil has no influence on the ratio, provided the water-supply in the soil does not fall below a certain concentration.

(ii) The concentration of water in the soil which is necessary for good development varies largely with the nature of the soil. Thus 10% in the Pusa soil is sufficient for the development of good plants though not the largest; in the Black Cotton soil 25% is too small for anything but the most meagre growth.

(iii) In the field, the action of the plant is to cause a marked decrease of concentration throughout a number of feet of soil.

(iv) This reduction of concentration was in the Pusa soil more or less uniform for about 5 or 6 ft. below which the change is smaller.

(v) A comparison of the observed decrease of water in a unit column of soil (after making an allowance for the water which evaporates directly from the soil into the air) with the weight of crops produced, yields a ratio closely approximating to that obtained by the pot-culture method.

(vi) Most of the water required by a crop is thus accounted for by the observed decrease of water within the root range. The amount of water which moves up from the sub-soil undetected is shown (page 271) to be necessarily small.

(vii) The soil within the root range is at harvest time frequently much more desiccated than it would be if it had been simply fallow. After the crop is removed there is a tendency for the water which moves up from below, to re-moisten this upper soil, but the process is certainly a very slow one.

(viii) The effect of a *kharif* (rains) crop in India will be in many cases the partial depletion of the water in the upper soil of the root range, whilst that in the soil below this stratum will be nearly or quite normal. If now such land be cultivated and sown with a *rabi* crop, the supply of water within

the root range will be defective, whilst that in the soil below is unable to assist the second crop, although the latter quantity is actually very large.

(ix) The whole of the facts which have been brought out by the experiments detailed in this memoir would be accounted for if the quantity of water which can move through a soil per unit time were dependent on the three factors, concentration, distance and physical character of the soil; temperature also no doubt has an important influence.

(x) There can be no doubt that if a laboratory method could be devised for the estimation of the soil's capacity for the "conduction" of water, such method would become of very great value to agriculture.

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